HIGH VOLTAGE OIL CIRCUIT BREAKERS

BY

ROY WILKINS, B.S., E.E.

Fellow, American Institute of Electrical Engineers;
Consulting Engineer, Pacific Electric Manufacturing Company

AND

E. A. CRELLIN, A.B., E.E.

Fellow, American Institute of Electrical Engineers;
Assistant Engineer, Division of Hydroelectric and Transmission Engineering, Pacific Gas and Electric Company

WITH AN INTRODUCTION BY

J. P. JOLLYMAN

FIRST EDITION

McGRAW-HILL BOOK COMPANY, INC.
NEW YORK: 370 SEVENTH AVENUE
LONDON: 6 & 8 BOUVERIE ST., E. C. 4
1930

3452.

INTRODUCTION

THE authors have set forth in this volume a chronological account of the development of the high-voltage oil circuit breaker, a discussion of the theory of its action, descriptions of modern forms, and an account of the results of many field tests. Acquaintance with the men who designed and constructed the first high-voltage oil circuit breakers and with the systems on which they were employed has enabled Messrs. Wilkins and Crellin to write an interesting and accurate history of this subject. Their technical training and operating experience enable them to discuss the theory and performance of the oil circuit breaker and its relation to the transmission system.

Descriptions of the modern high-voltage oil circuit breakers are given in considerable detail. Recent developments in operating mechanisms designed to meet the demands for greater speed and better control are presented and discussed. Field tests of performance of a number of different breakers are presented and reviewed. The tests made with relatively high charging currents are particularly interesting, since such conditions can be obtained only in the field. While the authors have treated their subject largely from the standpoint of the user, the viewpoint of the manufacturer has not been overlooked.

This book fills a long-felt need for a comprehensive treatment of the high-voltage oil circuit breaker and should prove of value to the student and engineer alike.

J. P. JOLLYMAN.

SAN FRANCISCO, CALIF.

ACKNOWLEDGMENT

The authors wish to acknowledge the valuable assistance of the several manufacturers and those individuals who have so kindly contributed and cooperated in making possible this treatise on the high-voltage oil circuit breaker. An attempt has been made to give credit in the individual quotations, but where due credit was not given the authors wish to take this opportunity to thank all those not specifically mentioned.

THE AUTHORS.

SAN FRANCISCO, CALIF.,
February, 1930.

CONTENTS

PART I

HISTORY

HIGH-VOLTAGE OIL CIRCUIT BREAKERS

CHAPTER I

EARLY TYPES OF SWITCHES IN GENERATING STATIONS

THE problem of switching was non-existent in the generating stations operating prior to 1890. They were small, isolated plants with a few short feeders serving consumers in the immediate vicinity of the plant. In general, their total output was used for lighting, and they were shut down during the daylight hours. A knife switch and a circuit breaker or fuse fulfilled all the requirements for the control of these small-capacity circuits.

The advent of the Niagara Power Company and the completion of the plant at Niagara Falls with its record-breaking 5,000-hp. generators presented the first real problem in switch design. Fuses and open knife switches were no longer suitable or safe, and engineers set to work to devise ways to protect the generators and the feeders radiating from the power house to the industries which had sprung up to take advantage of the power being generated by the waters of the big cataract. By 1893, there had been developed a 5,000-hp., two-way, four-pole, pneumatically operated switch for controlling the 2,300-volt circuits. Note that the switch was rated in horsepower, no other method of rating having as yet been devised. This switch was a cumbersome device and occupied a considerable floor area. It is shown in Fig. 1, which was made from a cut of a photograph taken before the switch was installed in the power house. As far as can be determined, this switch represents

the first example of a *multiple-break* switch, wherein one break was equipped with a shunt resistance for decreasing the current before making the final break. It is interesting to note that this idea has been revived and is now being used by some of the European manufacturers of modern switches, as will be pointed out under the description of modern oil circuit breakers. The contacts of this switch were made of a special non-arcing metal, and the installation

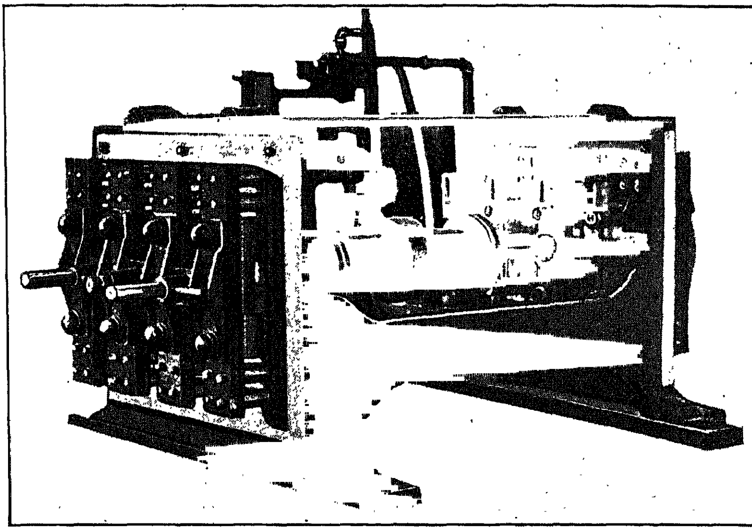


FIG. 1.—Five thousand "horsepower," 2,300-volt, four-pole, double-throw, pneumatically operated air-break switch.

in the Niagara Power House gave the switch a thorough service test during the year 1894.

One of the defects in the switch just described was the lack of barriers or isolation of the contacts of the several phases and the consequent danger of phase-to-phase arcing when loads were interrupted. To overcome this difficulty, the Stanley Electric Company, about 1894, manufactured and sold a switch which is illustrated in Fig. 2. This switch was a hand-operated air switch in which each jaw was in a separate insulated box provided with a shutter operated by

a spring. The contacts parted inside the box and the shutter snapped closed as the blade was withdrawn to cut off the arc and completely enclose the live parts of the switch, preventing a phase-to-phase short circuit.

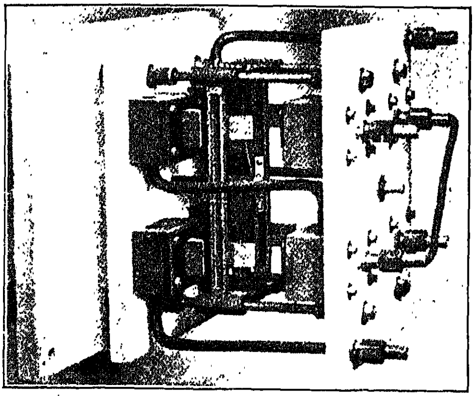


Fig. 2.—Stanley Electric Company double-pole, double-throw air-break switch, rear view.

These early types of switches are interesting in that they illustrate the methods employed by the earlier engineers to meet the problems of the day. They were the forefathers of our present-day switches and show that the pioneers had a switch problem to meet which to them, with their lack of precedent, was probably a problem as difficult as our own. In 1895, the electrical industry was only sixteen years old but had already made a remarkable growth. From the small plant sufficient only for a few scattered lamps, it had grown to the Niagara Plant with its 5,000-hp., 2,300-volt generators supplying a rapidly growing industrial demand, and the limit of air-break switches had already been reached.

EARLY OIL CIRCUIT BREAKERS

The exact date on which the first oil circuit breaker was put into service is hard to determine. Dr. Ing. H. C. Vogelsang, chief engineer of Voigt and Haeffner Aktien-Gesellschaft (Germany), states that in Europe the oil circuit breaker is credited to C. E. L. Brown of the Brown Boveri Company. This breaker was designed by him and built at Paderno in 1898. About this same time, Ferranti also built a switch that "first broke the circuit in air and then

completed the opening under oil." This differed from the Brown switch, which "opened the circuit completely under oil." The same source of information states that little work and development on oil circuit breakers was furthered in Europe after 1898 and that about 1900 and 1901 American-manufactured oil circuit breakers began to appear in Europe.

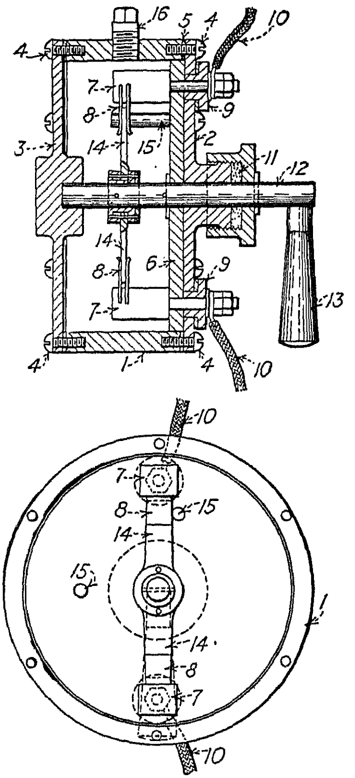


Fig. 3.—Drawing of an oil switch, patent application in 1894.

If Dr. Vogelsang be correct in attributing the first European oil circuit breaker to Mr. Brown, in 1898, then American engineers can claim a prior invention. United States Patent 508,652, dated Nov. 14, 1893, issued to Elihu Thomson, shows a diagram of an electric cutout in which one of the features of the invention is that, while the contacting surfaces, when the cutout is closed, are above the surface of an oil, the interruption of the circuit is accomplished by drawing open the contact pieces and drawing one or both of them down into the oil, which extinguishes the arc. This appears to read very closely along the lines of the Ferranti idea.

Alexander Wurtz, a Westinghouse engineer, obtained a patent on a non-arcing switch from his petition of 1894 in which he broke a circuit under oil, utilizing a "suppressor" principle. Figure 3 was made from a reproduction of the drawing accompanying the original petition for letters patent. This is the earliest example of an oil switch of

which it has been possible to secure an illustration, and it is quite remarkable to note the resemblance of the first horizontal-break, 60,000-volt oil circuit breaker to the principle of this switch. It has not been possible to secure definite evidence as to the date when the first oil circuit breaker went into actual service, but it was apparently some time in 1894 or 1895.

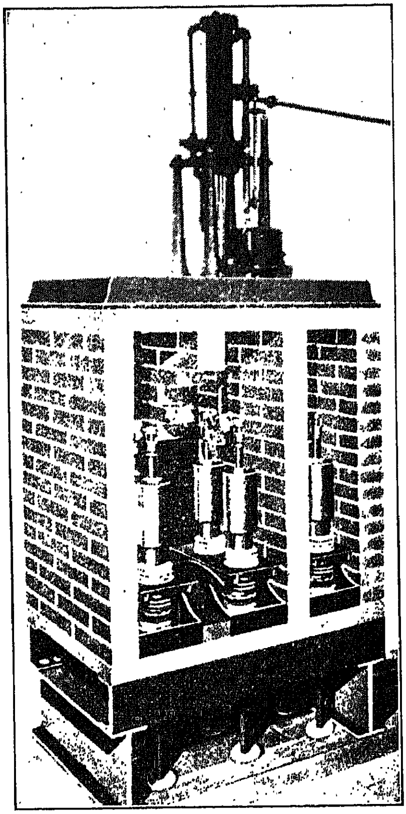


FIG. 4.—General Electric type H, 12,000-volt, three-pole, pneumatically operated oil circuit breaker.

By 1897, there had been developed and put in service pneumatically operated oil circuit breakers designed and built by the General Electric Company. These breakers consisted essentially of two insulated metallic tanks, usually of brass, with the circuit completed through two rods on a cross-arm and arranged to move up and down in a vertical plane. A switch of this type which was installed on a 6,000-volt circuit of the Metropolitan Railway Company, New York, is illustrated in Fig. 4, and Fig. 5 shows a similar switch, except that it is motor operated, which was used on the 12,000-volt lines of the Manhattan Railway Company in New York City.

In this switch, the individual phases were usually separated by brick or tile barrier walls, with the operating mechanism mounted above. The oil-filled cylinders in themselves formed the switch terminals, and the circuit was completed through a laminated-copper contact which

bridged across between the two cylinders or "pots," as they were usually called. The laminated-copper contact formed the main current-carrying part but did not first complete or interrupt the circuit, this function being transferred to the

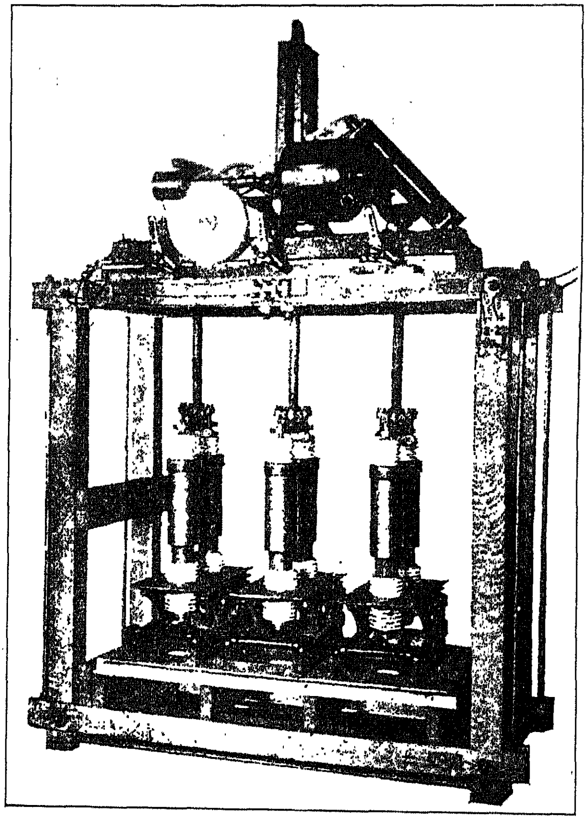


FIG. 5.—General Electric type H, 12,000-volt, three-pole, motor-operated oil circuit breaker.

secondary contacts, which consisted of two rods or bayonets entering expanding ring contacts submerged in the oil inside the pots. (In small current-carrying capacity switches, the brush contacts were omitted, the bayonets serving the double purpose of carrying the current and breaking the circuit.) Thus, the heavy current-carrying contacts were

much like the ordinary direct-current air circuit breaker and were relieved of all actual interrupting duty, keeping the contact surfaces free from pitting and in good current-carrying condition. The bayonets completed the final break, which was made under oil.

This switch has been described in considerable detail, as it is of more than passing interest. It is now more than 30 years since it was first developed, and yet the type is still in use in substantially its original form. Many improvements have been made, but the old form remains unchanged. The switch is now known as the General Electric "type H" breaker and represents that company's theory of high-duty oil circuit breaker design. This theory will be discussed in connection with the description of the General Electric Company's modern high-voltage breakers.

Thus far, the breakers described have been for circuits with a maximum potential of 12,000 volts. Such breakers are now classed as low-voltage oil circuit breakers, and it is not the purpose of this text to consider oil circuit breakers of this class. They present an entirely different problem. In general, the currents to be handled by such breakers are large and the voltages low enough so that the problem of insulation is relatively easy of solution. The problem is simplified by the absence of extreme voltages, but with the ever increasing capacity of generating stations and system networks, the problem of interrupting capacity is a serious one, and constant study and research are necessary to keep breaker design abreast of the demands for increased interrupting capacity.

CHAPTER II

THE FIRST HIGH-VOLTAGE SWITCHES

CALIFORNIA and the Pacific Coast is the real birthplace of the high-voltage oil circuit breaker. In the Eastern states, distances between generating plants and load centers were small, and there was no demand for extreme voltages. In California, the opposite was true. The vast hydroelectric resources of that state are to be found in the mountains, remote from power markets. Here was a situation requiring voltages much higher than had been used in the eastern part of the United States if the power was to be economically delivered to the consumer.

Beginning about 1898, transmission voltages in California started their upward climb, and the long lines began to make their appearance. The generator capacities were relatively small, and the kilovolt-amperes to be ruptured, low, but the insulation requirements for the switches presented a real problem. No switch for potentials higher than 12,000 volts had been developed, and the engineers designing the high-voltage transmission lines were forced to pioneer in an unexplored field. Nothing was known regarding transmission-line performance. There were no formulæ for calculating voltage surges, line regulation, and the many problems incidental to the operation of a long transmission line. Practically everything was reasoned out according to the best logic and electrical knowledge at the command of the engineer planning the project, and then it was put into operation and the results observed. There seems to have been a general feeling that an oil circuit breaker would interrupt a high-tension circuit too abruptly. At any rate, it is a significant fact that no advantage was taken of the

development of the oil switch by manufacturers in the eastern part of the United States, and all early high-tension lines were equipped with air switches or combinations of a switch and fuse. None of the electrical manufacturers would make and guarantee an oil switch for potentials in excess

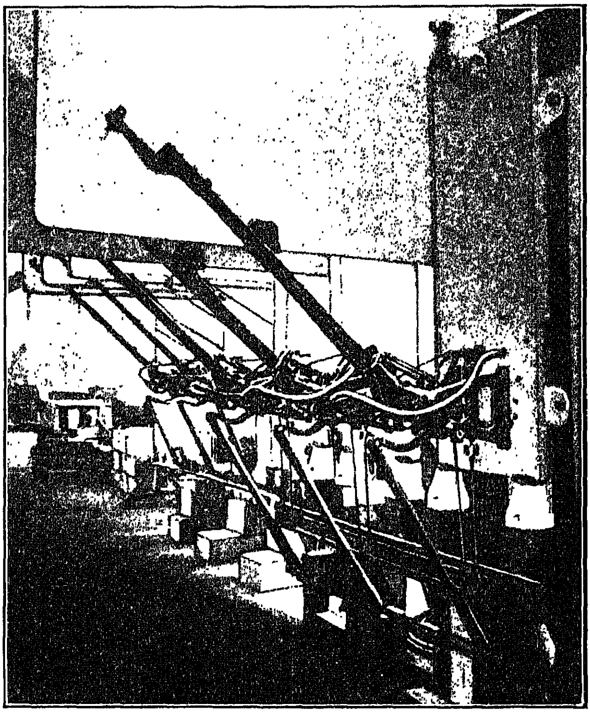


FIG. 6.—Westinghouse 25,000-volt, three-pole, pneumatically operated air-circuit breaker.

of 12,000 or 15,000 volts but offered, instead, various types of air-break switches.

A 25,000-volt switch as manufactured by the Westinghouse Company about 1898 to 1900 is shown in Fig. 6. In general construction and action it resembles a greatly magnified three-pole circuit breaker of the type now common for the control of direct-current circuits. Barriers were interposed between the several phases to prevent the arc

traveling sidewise and causing a phase-to-phase short circuit. Figure 7 shows another Westinghouse product, a 40,000-volt combined fuse and switch. This switch represents the first type of overload protection employed on high-voltage lines and is nothing more nor less than an open fuse arranged to operate, also, as a disconnecting switch. The fuse wire is plainly seen in the illustration. The right-hand member was a conductor and was hinged at the bottom. It was held in an almost vertical position by the fuse wire which completed the circuit to the terminal at the top of the marble panel. The long vertical member was of insulating material and hinged at the same point as the previously mentioned member. This vertical rod could be operated by hand to open the switch by separating the contacts at the top. On overload the fuse wire would melt, thus freeing the right-hand member at the top and permitting it to swing through a great arc and finally hang vertically downward. The arc following the blowing of the fuse would rise and finally be broken by the increasing distance between the two terminals.

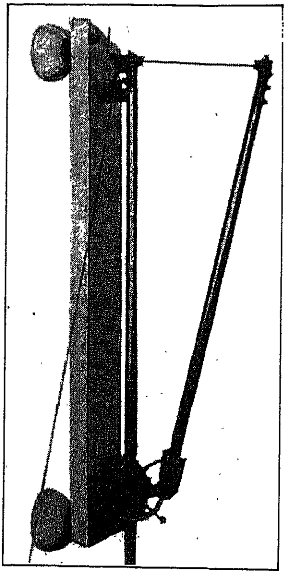


FIG. 7.—Westinghouse 40,000-volt "stick-type," single-pole combined switch and fuse.

Switches of the type just described were used by the Mount Whitney Power Company on its 30,000-volt lines in Southern California. They had a 36-in. break and were installed with 30-in. separation between phases. The Snoqualmie Falls Power Company in Washington also used similar switches with a 48-in. break for its 36,000-volt lines. The fused type of switch was likewise used in some of the plants now a part of the Pacific Gas and Electric System in California, and a few still remain in service in Alta Power

House, where, until very recently, they were used for the protection of a 26,500-volt circuit. The operators in that plant have added one new feature to the switch, and that is a wooden member held in front of the switch to limit the travel of the moving arm and, thus, prevent its striking the operator on the top of the head should he inadvertantly be standing too close when the fuse opened the circuit and released the arm.

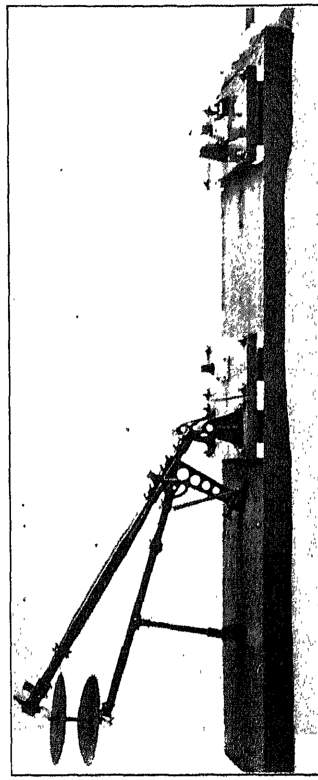


FIG. 8. — Stanley 40,000-volt, single-pole combination switch and fuse.

Another switch of the type just described is shown in Fig. 8. This switch was built by the Stanley Electric Company for use on 40,000-volt circuits and shows very clearly the design and method of operation. Switches of this type were used by the Standard Electric Company and the Bay Counties Power Company on the early transmission lines built to supply the district around San Francisco Bay.

The disadvantages of the type of switch just described are obvious. Numerous attempts were made to improve upon its action or devise a switch of different type with better characteristics. The swinging arm depended solely upon gravity for its action, and, as a result, it was slow in getting started on its opening stroke and permitted the arc to hold on for a considerable time. Fires were inevitable and numerous disastrous ones occurred.

A hand-operated, spring-actuated, quick-break air-break switch, devised by the late John Martin and used on the

lines of the Yuba Power Company in California in 1898, is illustrated in Fig. 9. The switch was mounted on a marble panel and its general arrangement and construction are well shown in the illustration. This switch was tested at 36,000 volts, and its action compared favorably with the switches

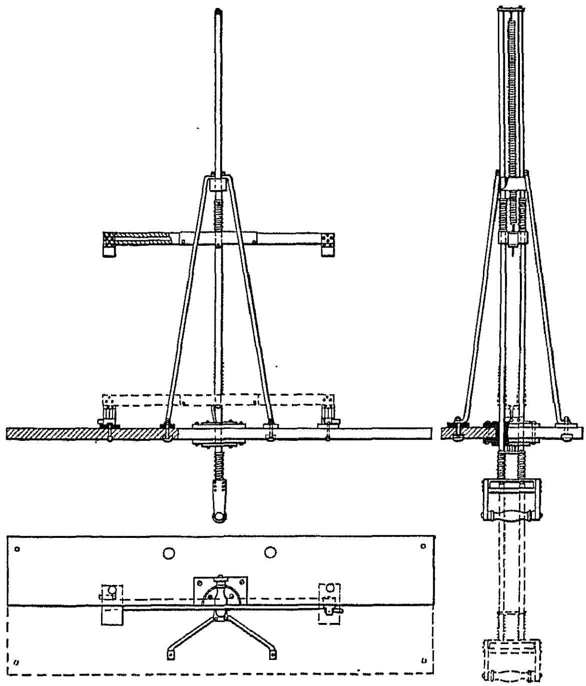


FIG. 9.—Martin 36,000-volt, quick-break air switch.

previously described, and it was successful in interrupting small currents.

Another type of accelerated break switch is shown in Fig. 10. This switch contained fuses carried in expulsion chambers which made use of the explosive force of the blown fuse to speed up the switch break. The tanks at the bottom of the switch acted as dashpots to bring the switch to rest. The closing rods were carried up through the tanks.

It was evident to all engineers and operating men engaged in the work of designing and operating these transmission systems that the switch problem was far from being solved. The open-air switches and fuses were inadequate and unsafe both to life and to property. They were incon-

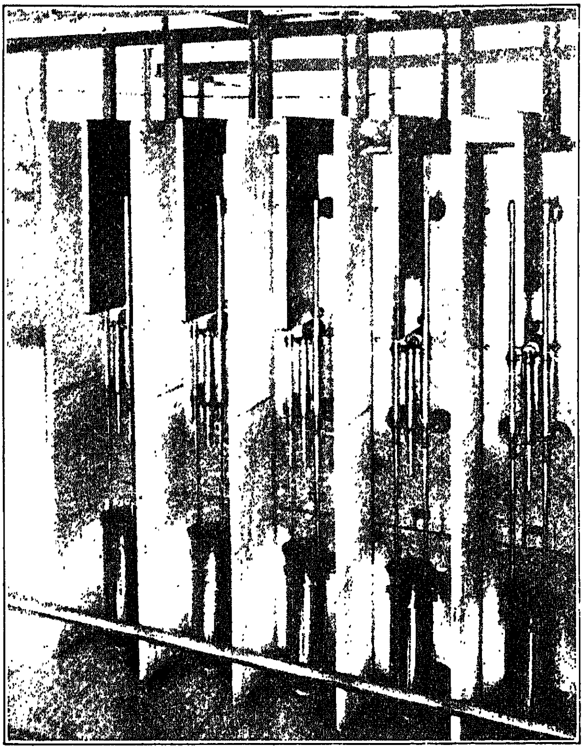


Fig. 10.—Fused switch, 22,000-volt expulsion type.

venient to operate, requiring considerable time for refusing before being ready for service after once having interrupted the circuit, and were the cause of several disastrous fires. The desirability of the oil switch, with its arc-suppressing feature, began to be more fully realized, but the problem of insulation was one not easily overcome. No suitable bushings or insulating tubes were available, and the manu-

facturers of electrical equipment were universally loath to offer an oil switch for such high voltages. With no factory-built switches obtainable, the engineers of the Pacific Coast set themselves to the task of designing and building an oil switch of their own, and it was this urgent necessity for a particular piece of equipment and the pioneer spirit of the West which led to the birth of the high-voltage oil circuit breaker.

CHAPTER III

THE FIRST HIGH-VOLTAGE OIL CIRCUIT BREAKERS

THE first switch for duty on a 40,000-volt line in which oil was used for suppressing the arc was built and tested by J. N. Kelman, then an employee of the Bay Counties Power Company in California and now president of the Kelman Electric and Manufacturing Company of Los Angeles. Mr. Kelman tested his switch in the summer of 1901 and has kindly furnished a description of the switch and tests, which is quoted direct from his letter:

At the time (1901), it was the general opinion of the leading engineers that an oil switch would open a high-voltage circuit too quickly, resulting in extreme surges in the line, and that a gradual opening was necessary. Therefore, I used a combination of water and oil with an upward vertical break which made the first break in water, thus introducing high resistance; then, as the blade moved upward, the water and oil would mix, making still higher resistance; and, finally, in the oil the circuit would be opened.

The first test switch consisted of an ordinary 50-gal. wooden barrel cut in two, each half being set on insulators, a contact placed in the bottom of each, and a cross-bar with long vertical blades connected across the top arranged to drop down into the contacts to close the circuit. The half barrels were filled with water to a point several inches above the contacts, then to the top with oil, thus giving visual evidence that the circuit was open (see Fig. 11).

The first tests were made on a 40-kv. line with 2,000-kw. generator, the single-pole switch being closed across one phase, then instantly opened so easily that tests were made at Colgate Power House with the entire power house of about 10,000 kw. behind, and, later, some tests were made at North Tower [substation], and some at the cement plant near Suisun.

The tests at North Tower were made with two small pickle kegs instead of the barrels, and the results were not so good,

although the circuit was safely opened each time. The kegs which were not fastened down would "dance" when the circuit was opened. The small size and the fact that the water was "briny" probably caused this.

The switches were made up on the water-and-oil principle and installed on the Bay lines in Colgate Power House in April, 1902. They had iron tanks about 20 in. in diameter and 30 in. deep, with an inner tank about 14 in. in diameter and 16 or 18 in. high, this tank being mounted on insulators so as to give an oil space all around it. The contact was placed in the center of this tank and it was partly filled with water, then oil on top of the water

FIG. 11.—The first 40,000-volt oil switch in service, 1901.

and in the outer tank. The top of the inner tank was several inches below the surface of the oil. There were no covers on the tanks.

The moving contacts were long, vertical blades attached to a cross-bar, which could be raised and lowered.

These switches were used continuously from April, 1902, until March, 1903. The operating practice was to tie the lines together with a light fuse at North Tower, all of the substations being carried on one line, the other line being what we called the "light" line, that is, no load on it between the power house and North Tower.

In the event of a short circuit, the fuse at North Tower would blow, and it was the practice instantly to jerk out the switch on the "light" line at the power house; then, if the trouble was still

on, the other switch would be jerked out. It was the practice then to test out the lines, one at a time, by closing the switch and instantly opening it if the short circuit was still on. From the time the switches were installed until 11 months later, this practice was continued, and the switches opened numerous short circuits successfully.

One day in March, 1903, the switches were opened at least five times in a very short space of time before they finally threw blazing oil on the woodwork, setting fire to the power house.

There were no oil switches to be had at the time these were installed, and when they were available later, the price was prohibitive, and the manufacturers would not recommend them for opening short circuits, as we were doing right along. Considering the state of the art at that time and how crudely the switches were made, their performance for 11 months was remarkably good. The only insulators used were ordinary line insulators. Had tubes been available so that covers could have been placed on the tanks, the fire might never have occurred.

After the fire, the water-and-oil combination was abandoned and work begun on a straight oil switch, the development of this being carried on for two or three years before switches were made for the market.

Some further data on the operation of these switches are contained in the following quotation from an article published in January, 1903, at which time they had been in service for approximately 8 months (1) [1]:

As the subject of high-tension switching is of considerable interest to electrical engineers generally and to those who have to handle long lines with their attendant high voltages particularly, it may be of interest to your readers to know that at the Colgate Power House of the Bay Counties Power Company, Yuba County, Calif., several circuits varying in length from 60 to 160 miles are run off the same set of 45,000-volt bus bars, and these circuits are switched in or out as easily and with as little disturbance as an ordinary low-voltage distributing circuit would cause.

There being no switch on the market that would do the work required, special oil switches were designed by the writer, and they handle the high voltage and heavy current so easily and satisfactorily that the power-house attendants think no more of opening

[1] This refers to the item with the corresponding number in the References, pp. 297–298.

a short circuit with 12,000 kw. behind it than they do of switching a generator on or off the 2,400-volt bus bars. The current flowing into a short circuit varies from 200 to 300 amp. at from 40,000 to 35,000 volts, depending on the nature of the short, the voltage normally carried being 45,000.

One of these switches, which has been in service over 6 months, has opened the circuit ninety-seven times in all with never less than 25 amp.; a number of times, 60 amp.; and six times under short circuit with from 200 to 300 amp.

So completely has the carbonizing of the oil been overcome that the oil in this switch, which has never been changed, is perfectly free from carbon and is as clear and good as the day it was put in. These switches have been given a more severe test than any other switch on the market today, being tested at 60,000 volts under short circuit with 2,000 kw. behind them. Three-pole switches are used, experience having proved that they are better than single pole.

At practically the same time that the oil and water break switch described by Mr. Kelman was being developed, R. H. Sterling, also an employee of the Bay Counties Power Company, was at work on the design of a two-break, horizontal-movement oil switch for use on the 60,000-volt transmission line from Colgate Power House to Oakland. This switch was constructed and tested as described by Mr. Sterling in a letter which is quoted, in part, as follows:

I built the first switch of this design at the substation, located at the Piedmont Power House where the then Bay Counties Power Company supplied the Oakland Traction Company with power. I was assisted in the mechanical work by the station operator (Milo T. Sipe). This was early in 1902. Some time in 1903, as I recall it, a public test was made of my switch and of one designed at the same time by J. N. Kelman, also an employee of the Bay Counties Power Company. The latter switch, however, used water instead of oil as the arc-breaking medium, and the blades had a perpendicular instead of horizontal action. I based my claim on this horizontal motion as a means of the arc breaking more readily by the natural upward direction it assumed as the blades or contacts separated than the upward throw of the blades in use on 2,200-volt oil switches, then being manufactured.

The test above referred to took place at the Golden Gate Cement Company's plant at Suisun at midnight. John Martin

and other officials were present. The line voltage at that time was about 45 kv., as we had not then stepped up to 60.

The test consisted in shorting the line with the full capacity of Colgate Power House on and suddenly opening the three-phase switch. My switch did this repeatedly and successfully. It was found, however, that there was some accumulative carbon in the oil, oil in those days, probably, not being of so good quality as now.

I am quite sure that there was no other oil switch proposed for 60 kv. at that time. I spent some months, in 1901, at the

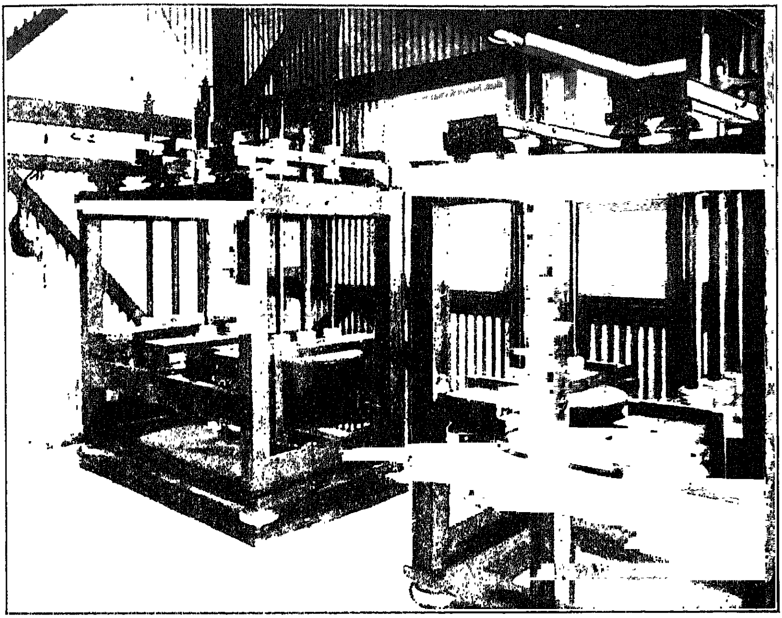


FIG. 12.—Stirling 60,000-volt oil switch, 1902.

Stanley Laboratory in Pittsfield, Mass., where the 60-kv. apparatus was being manufactured for the two, then, highest-voltage plants in the country—the Bay Counties and the Standard Electric—and the requirements for a switch of this kind were not thought of, and it was only after my experience in transmission work, when I came to California, that I saw the need of one. The plain disconnect switch, previous to this, was considered to fill all wants. The idea of cutting out a bank of transformers seemed to have been overlooked. I am enclosing a photograph of the first set of switches I made for the Piedmont substation.

A reproduction of this photograph is shown in Fig. 12.

The horizontal rotating break switches of the type described by Sterling proved the most popular for use on the lines in California, and improvements on the original design were soon forthcoming. One of the principal changes was to increase the number of breaks in series per phase from two to four. These switches are described by F. G. Baum in an article (2) published in November, 1904, as follows:

That the oil switch is the only one that will stand heavy duty has been amply demonstrated. As it has not been possible to purchase satisfactory switches in the market, I have designed a line of switches for our high-potential work.

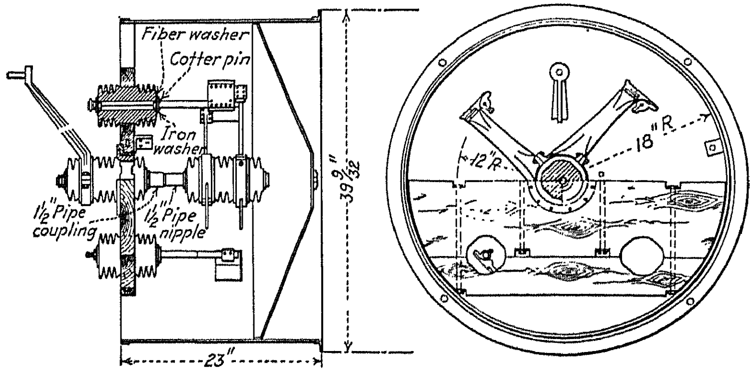


FIG. 13.—Baum 60,000-volt, four-break oil switch, 1903–1904.

We are now using the switches shown in Fig. 13 at our power-houses designed to handle from 10,000 to 40,000 kw. at 50,000 or 60,000 volts. Each pole is in a separate tank and mounted in a fireproof compartment. The three poles are operated together. The switch as shown has four breaks per leg.

On less important work we use the two-break switch. This is a very simple and inexpensive design but answers all purposes as well as more elaborate switches.

Switches having the same operating principle but mounted differently, designed by R. H. Sterling, have been in service on the system for several years and have given very good results.

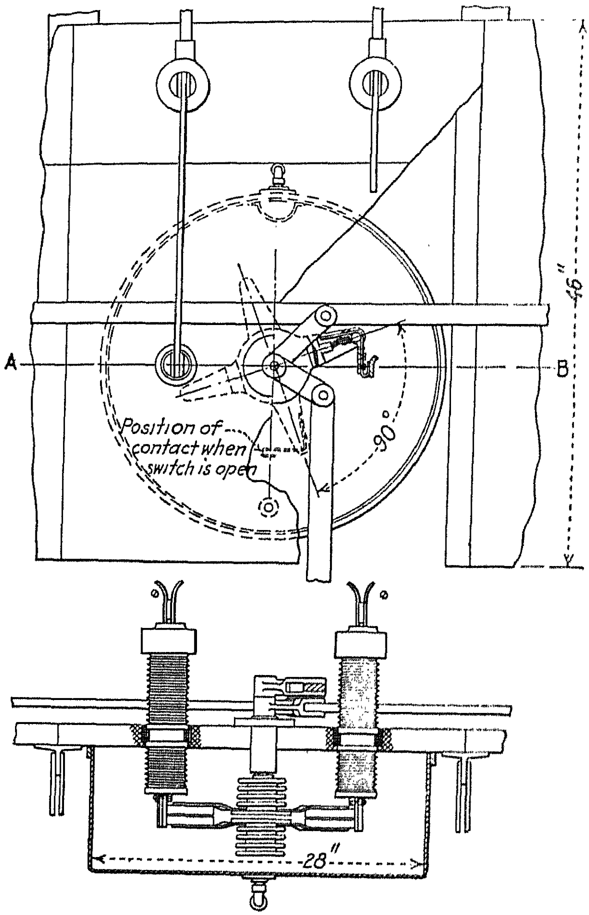
The tests and development of oil switches by the engineers of the West for use on 60,000-volt lines focused attention

on this class of apparatus and made it apparent to the manufacturers that there was to be an active demand for such equipment. Even so, they rather hesitated to quote on switches for such voltages, and it was only upon the insistent demand of the late John Martin, then Western representative of the S. K. C. Company (Stanley, Kelly, Chesney Company), that his principals finally built a switch and sent it out to be tested. The switch arrived in time to be included in the series of oil-switch tests made on the Kelman oil switch, and as Mr. Kelman was present to witness the tests, he has included a description of the switch and tests in his letter, which is quoted as follows:

> At the same time, tests were made with an experimental oil switch, sent out by the Stanley Electric Company, this switch consisting of two porcelain cylinders about 4 or 5 in. inside diameter and about 20 in. deep with round vertical rods carried in a cross-bar and dropped into the contacts to close the circuit.
>
> This was the first test made with an all oil switch, and it opened the circuit three times very easily; then, the fourth time, it threw the oil out; and, after that, it threw the oil out each time. Mineral seal oil was used for the first test, and then Transil oil was tried, also.

In order to present the picture of this switch a little more clearly, it will be necessary to amplify Mr. Kelman's description. The switch consisted of two insulated metallic tanks filled with oil. Inside each tank and raised slightly from the bottom was one of the porcelain cylinders referred to by Mr. Kelman. The switch contacts were mounted in the bottom of these porcelain cylinders and the leads were simple wires carried from the bottom of the cylinder up through the oil between the outside of the cylinder and the tank. The circuit through the switch was completed by means of a pair of bayonet contacts carried on a cross-head and arranged for up-and-down movement inside the porcelain cylinders. The tips of the bayonets were above the top of the porcelain cylinders when the switch was in the open position. This switch was never offered for sale.

The Stanley Company then built a switch with a horizontal rotary break and sent it out for test. It was installed



Front Elevation, Section of Tank and Slab on Line A-B

FIG. 14.—Stanley 60,000-volt oil switch.

at Mission San Jose substation and tested out on the lines of the Standard Electric Company. The general construction is shown in Fig. 14. Mr. Chesney has described these tests in a discussion on "Oil Switches for High Pressure" (3),

wherein he states that the switch successfully interrupted three-phase short circuits on both the receiving end and the generating end of the 46,000-volt transmission line with a connected generator capacity of 11,000 kw. This was the first successful commercial high-voltage oil circuit breaker, and it is interesting to note that one of this type is still in service in the Alto Power House of the Northwestern Pacific Railroad in Marin County, Calif., where it is used in connection with the electric service supply from the lines of the Pacific Gas and Electric Company.

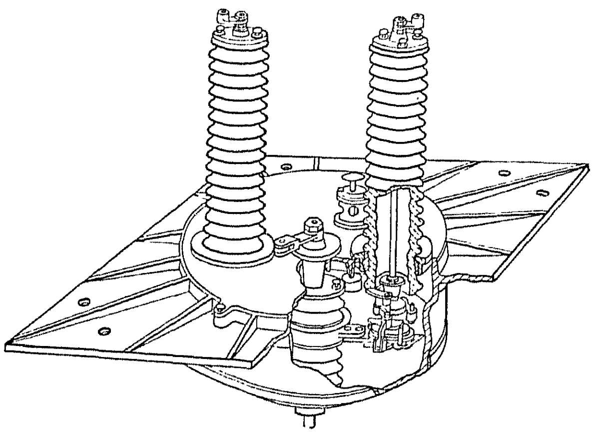


FIG. 15.—Stanley 60,000-volt oil switch, as illustrated in their 1903 catalogue.

The Stanley Company was the recognized leader in high-tension work, and it was to them that the operating engineers naturally appealed for help in circuit-breaker manufacture, offering, as proof of feasibility, designs of breakers already in daily use. The final result was a breaker along the general lines of the Sterling breaker with porcelain bushings and a cast-iron cover, features not available in competing equipment for several years.

A reproduction of an illustration in the 1903 catalogue of the Stanley Company is shown in Fig. 15 and shows the type of switch sold by them.

Some further descriptions of tests conducted on the locally built oil switches are recorded by F. A. C. Perrine in the same series of oil-switch discussions (4) and confirm the successful operation of the early oil circuit breakers built by the engineers of the operating companies from designs of their own and from such materials as they found available for the construction of such apparatus.

It is interesting to note that even as late as 1904 there was still doubt in the minds of prominent electrical engineers as to the practicability of oil circuit breakers for high voltages. In the discussion of oil circuit breakers just referred to, Ralph D. Mershon, later president of the American Institute of Electrical Engineers (1912–1913), stated that he was not yet convinced that the day of the high-voltage oil circuit breaker had arrived. Its usefulness, however, had been definitely proved to Western engineers, and its development was carried on by the power companies as well as by the manufacturing companies.

The General Electric Company had developed the type H switch for successful use on 15,000-volt circuits and, naturally, turned to this design for use at the higher voltages. The difficulties of insulation were considerable but were overcome by mounting each "pot" on four wooden legs, as shown in Fig. 16. The switches shown in Fig. 16 were purchased by the Puget Sound Power and Light Company (Washington), in 1903, and were installed in the Massachusetts Street substation of that company in Seattle, in the year 1904. They continued in service at 60,000 volts until January, 1929, when they were removed during extensive reconstruction of the station.

The type H switch is normally a "live-tank" switch, although, in the case of the 60,000-volt switches, the "pots" were made of wooden staves held together with twine. The difficulty of complete insulation from ground at voltages of 60 kv., together with oil leakage and the general rather awkward arrangement from an installation standpoint, led to the final abandonment of the original type H form for

use at this voltage and the adoption of the drop-bar type of switch. These are illustrated in Fig. 21 and are further described in the discussion of the 100-kv. switches.

The Westinghouse Company for a long time advocated the air-break switch of the type shown in Figs. 6 and 7

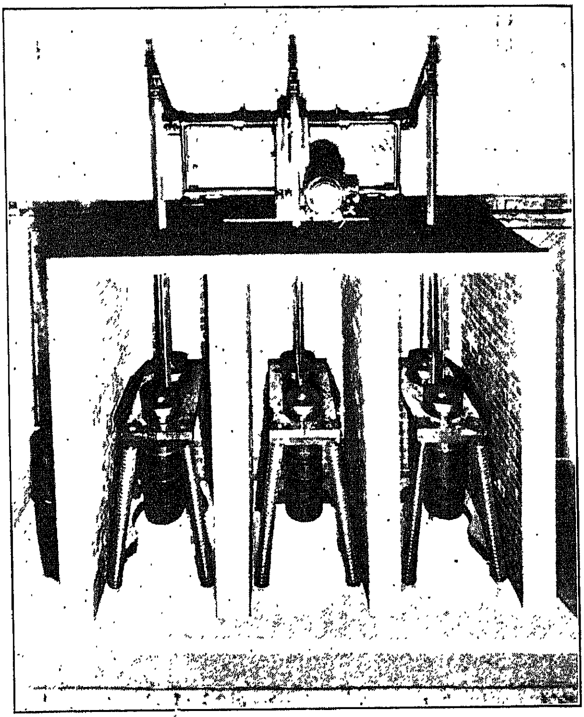


FIG. 16.—General Electric type F, form H-3, 60,000 volts, 400 amp. Purchased by Puget Sound Power and Light Company in 1903 and installed in Massachusetts Street substation, Seattle, Wash., in 1904; dismantled January, 1929.

but later adopted the drop-bar solenoid-operated type, designated in the high-tension class as "type G." Several of these were installed about 1906 (see Fig. 17). Early Westinghouse bushings were built of tape, varnished cambric, and mica wrapping, and the circuit-breaker tops were soapstone. The contacts were of the flat-butt type.

Upon the introduction of the condenser bushing proposed originally by Rudolph Nagel, the problem of lead insulation

was greatly simplified, the covers were changed to cast iron, and the voltage was raised, as required, to 110 kv. (5, 6).

Between 1909 and 1911, there were several outdoor installations of oil switches, among them the Niagara Lockport and Ontario at 66,000 and the Southern Power at 110,000 volts. It is notable that the physical form and general arrangement have not greatly changed since that time.

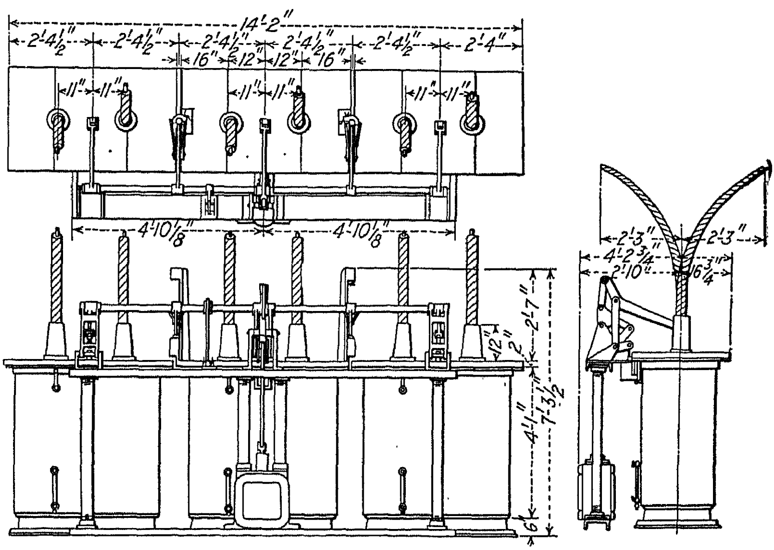


FIG. 17.—Westinghouse 60,000-volt, solenoid-operated, type G oil switch.

In Europe, the first 40,000-volt transmission (at Gromo in 1905) was equipped at the power-house end with Brown Boveri oil circuit breakers. The demand for the higher transmission voltages abroad was not so great, however, and the lead in development was rapidly taken by the American manufacturers.

Refinements were added as rapidly as insulating and other materials were made available, and the switches became more and more reliable. The drafting-room files of the Pacific Gas and Electric Company contain an interest-

ing record of the changes and betterments in design. The earliest drawing of a 60-kv. switch recorded bears the date of Nov. 28, 1903, and successive designs, each superseding the previous one, carry the story up to the latest drawing of Dec. 30, 1925, which was later revised, Oct. 27, 1926, to represent the final design of the 60-kv. oil circuit breaker then being constructed by that company in its own shops

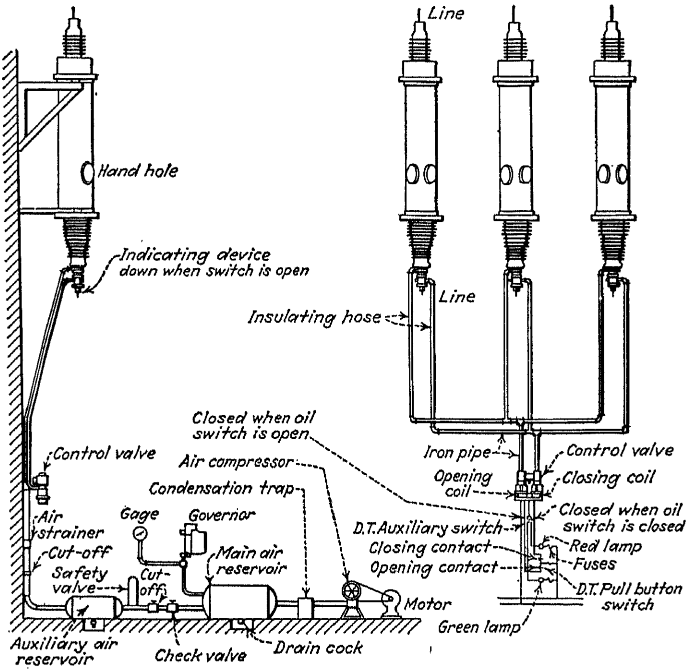


FIG. 18.—General Electric 100,000-volt, type T, pneumatically operated oil switch.

for light operating duties in the smaller transmission substations.

As the voltages used for transmission increased, circuit breakers for higher-voltage duty were designed, and in 1908 the first 100-kv. oil circuit breakers made their appearance. These were the General Electric Company's type T breakers, credited to Hewlett and shown in Figs. 18, 19, and 20. Installations of these breakers are to be found in Stanislaus

Power House of the Sierra and San Francisco Power Company (now part of the Pacific Gas and Electric System) and in the Big Bend Power House of the Great Western Power Company.

It is at once apparent from the illustrations that this breaker represented a radical departure in design from those previously built for lower voltages. Each pole of the breaker consists of a steel cylinder approximately 20 in. in diameter and 7 ft. 10 in. in length mounted in a vertical position on a wall bracket. A header in each end supports the bushings, and the cylinder is filled with oil to within 12 in. of the top.

The switch is pneumatically operated with air supplied through two long insulating rubber-hose connections. The

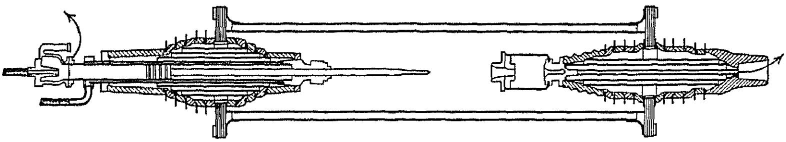


FIG. 19.—Detail of single pole of General Electric type T oil switch.

lower bushing contains the operating mechanism, which consists of a bayonet contact with a piston at one end. To close the switch, air is admitted to the bottom side of the piston, and it is forced upward. In opening, air is admitted to the upper side of the piston through the space between two concentric cylinders, and the bayonet is forced downward. The upper bushing supports the contact, which is very similar in character to the explosion-chamber contacts described under Modern High-voltage Oil Circuit Breakers.

Electrically, this was a very good circuit breaker, but it had many mechanical imperfections. One of the most serious defects in the type T breaker was the leakage of oil into the bottom of the operating cylinder when the switch was in the closed position. When an attempt was made to open the circuit, the piston movement would be blocked by the collection of oil. As a result, the contacts would

not be opened far enough to break the arc, and it would hold on and cause considerable damage. Also, the breaker was difficult to keep oil-tight and continually leaked oil

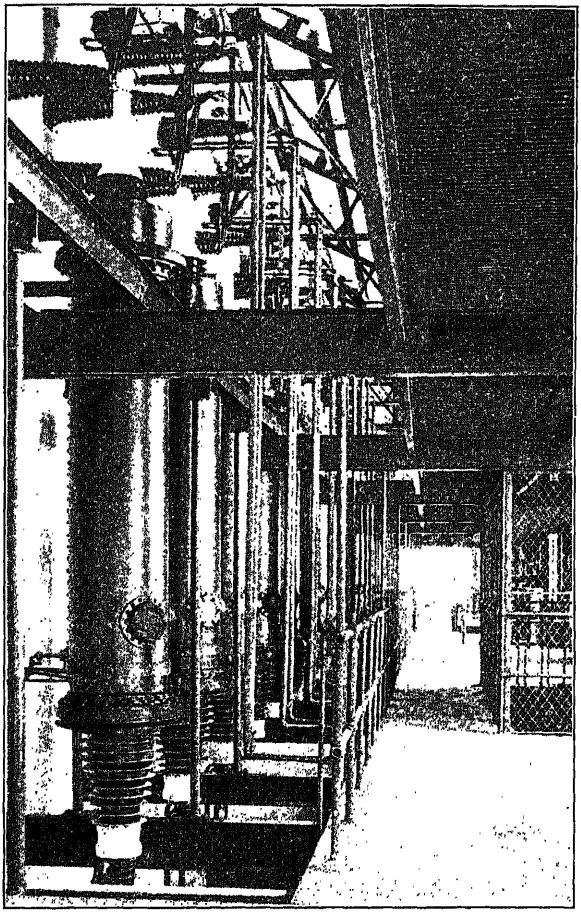


Fig. 20.—An installation of General Electric 100,000-volt type T oil switches.

on to the floor below. The contacts were extremely difficult to align. In order to inspect and repair the upper contacts, it was necessary to remove the upper bushing with the attached contacts, and, upon reassembling, great care had to be exercised to insure proper alignment for good operation.

The many difficulties experienced in the operation of the type T switches caused the General Electric Company to turn to still another design, and almost before the type T switches were in service, they were made obsolete by the introduction of the type K–10 switch shown in Fig. 21. This switch followed the general design of some of the low-voltage switches which had been manufactured for several years, the principal changes being in size and lead-in bush-

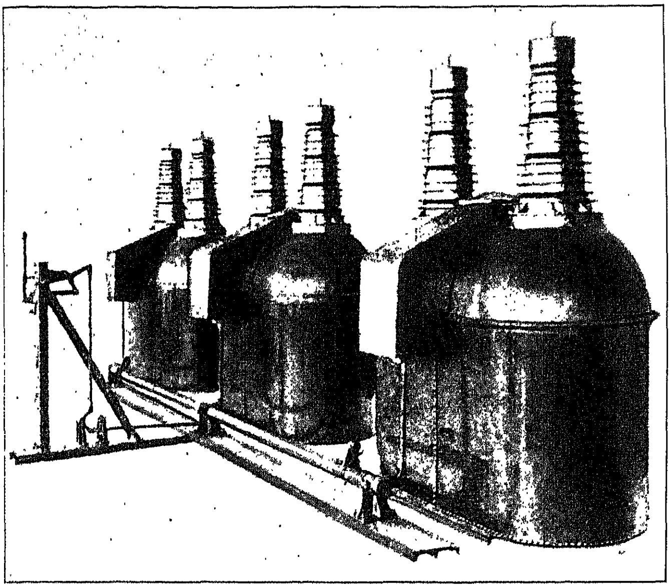


Fig. 21.—General Electric 100,000-volt type K–10 oil switch.

ings. The bushings were built up from fiber or paper tubes and washers impregnated with a resinous or bituminous compound, and were suitable only for indoor use. Contacts were of the wedge-and-finger type. As the requirements for increased rupturing capacity became factors in oil-switch design, the General Electric Company again turned to the type H switch and added the principle of the explosion chamber to the contacts of its type K switches for heavy duty. These will be described later. Further

steps in the refinement of the type K–10 switch shown in Fig. 21 were the addition of a porcelain shell or weather shed to the bushing and, finally, the replacement of the resinous compound by oil, thus producing the familiar oil-filled, high-tension bushing of present-day General Electric oil switches.

The transition to the higher voltages followed the introduction of the suspension-type insulator in 1907, for prior to that time it had not been practical to operate above an upper limit of 80,000 volts with the pin-type insulators then offered by the insulator manufacturer. With better line insulators available, the next step in oil-switch design was to make the breaker terminal bushings weather proof and the tank and cover water-tight, in order to fit them for outdoor service. By 1910, there were available outdoor breakers for the highest voltages used in practice.

From the year 1910 to the present, there has been a constant improvement in oil circuit breakers, and design has followed the increasing transmission voltages. Space does not permit of a full description of the various types of high-voltage breakers installed in the past 20 years. They were, generally speaking, of the same appearance as present-day breakers, the individual oil tanks for each phase being universally used with bushings projecting upward through the cover. The mechanism, in some cases, completed the circuit by an up-and-down motion in a vertical plane and, in others, by a rotating or linear motion in a horizontal plane. Improvements in bushings, contacts, and operating mechanisms were being constantly made, but the original form remained. In 1923, the first 220-kv. breakers were placed in service, and these now represent the highest-voltage oil circuit breakers in commercial use on transmission systems. They will be more fully discussed later under Modern High-voltage Oil Circuit Breakers.

It is realized that this history of the oil circuit breaker is far from complete. It had of necessity to be so, owing to the limitations of space in this text. A large and very interesting volume could be written on the subject, but for

the purpose of this study it has been thought best to touch only on the principal milestones along the road of progress, rather than to attempt any lengthy study of the many types and makes of oil circuit breakers developed to meet the rapidly growing demand for this class of equipment. The point at which we are striving to arrive is a comparison of the breakers now offered by the manufacturers, together with information as to their design, construction, and performance in actual service. The history just reviewed will serve as a backgound for further study and pave the way for a full description of the best designs offered in modern breakers.

PART II

THEORY AND DISCUSSION

CHAPTER IV

THE ARC

All equipment now available for the interrupting of a high-voltage electrical circuit under load produces an arc at the point where the circuit is broken. The suppression of this arc and the reduction of its duration to the minimum possible time are the principal problems of design in apparatus for the protection and control of electrical circuits. Under these conditions, a study of the arc itself and of its action and nature under the conditions found in circuit breakers is of the utmost importance if the problem is to be attacked intelligently.

It is only within the past decade that the fundamental principles governing arc formation and character have, in some measure, become understood. Physicists and research men have been working on the underlying principles for the last twenty years or more, but the designing engineer has been slow to apply the knowledge available and realize and understand its importance. Many minds are now at work on this particular study, and important new developments are being announced from time to time.

Fundamentally, an arc is a stream of ions and electrons between two conducting surfaces at different potentials. Usually, the stream is made up of ionized gases of the material of the two electrodes and the surrounding medium, although examples can be found where either one alone makes up the major portion of the conduction, such as the tungsten arc lamp, where the arc is of tungsten vapor in an evacuated vessel, or the well-known mercury arc, where the arc stream is mercury vapor between graphite electrodes.

The process by which a gas conducts a current is

1. The ionzation of the gas by an external agent such as heat or a potential stress. By this means, an electron is liberated from a molecule of the gas, leaving as the residue a positive ion.

2. The electron and positive ion acquire energy under the action of an electric force (difference of potential).

3. Additional ionization by collision is caused by virtue of the rapidly moving ions and electrons.

The current passed through the gas between a pair of electrodes is a measure of the sum of the charges carried by the electrons and ions, and as long as the potential between the electrodes remains constant, ionization will increase, causing more and more heat and further ionization by virtue of increased activity and collision between ions and molecules and consequent multiplication of ions and electrons. For this reason, an arc has a negative resistance characteristic; that is, its resistance drops with increased current.

The number of electrons normally existing in air is relatively small, to the order of 1,000 per cubic centimeter, and they are forming and recombining at the rate of about 20 per second, thus maintaining an approximate balance. This number of free electrons is insufficient to cause breakdown in air between electrodes at different potentials where the stress is less than 30,000 volts per centimeter, and, consequently, ionization must be started by an external source. There are numerous ways of causing ionization, but, for the purpose of this study, only two of these means need be considered. They are a high electrical potential gradient and heat.

If sufficient potential gradient is applied to even the best-known insulating mediums, a current will flow by virtue of the few electrons initially present, and the action described for gases then follows as soon as sufficient heat is available to ionize a conducting path. Under oil, the action is similar. The oil has a cooling effect on the arc, but if the potential gradient is sufficiently high to cause a current to flow, the

oil breaks down to supply various complicated gases for ionization in addition to the ionized material from the electrodes.

The common cause for the start of ionization when the contacts of an oil circuit breaker part is localized heating. With the breaker in the closed position, the electrodes are in metallic contact and carrying current. As they begin to separate, the area of contact is gradually reduced, and the current density is increased proportionately, finally reaching a point where there is sufficient current density to cause excessive heating and consequent ionization. The exact process of this initial ionization has not yet been definitely established. That it is due to heat, there can be no doubt, but whether ionization is first started due to the metal in the electrodes reaching the boiling point, or whether the contacts reach a temperature sufficiently high to cause ionization in some of the surrounding media, or whether the ionization starts from a minute disruptive discharge at the instant of separation of the contacts is still to be determined.

For the purpose of this study, it is sufficient to know that ionization takes place and an arc is formed whenever the contacts of an oil circuit breaker part, if a sufficient potential is maintained between the contacts (7).

It must be borne clearly in mind that the ionization takes place in the gas immediately surrounding the electrodes and not in the metal of the electrodes themselves. This fact has been clearly demonstrated in experiments with vacuum switches in which the contacts were parted in an extremely high vacuum. With the contact chamber sufficiently exhausted, the switch contacts were able to interrupt fairly large currents (1,000 amp.) under potentials as high as 40,000 volts without continued arcing. A very small amount of gas in the contact chamber, however, rendered the switch inoperative, due to arcing. In order to operate the switch successfully, it was necessary to free the electrodes themselves of absorbed gases and maintain an exceedingly high vacuum at the time of opening the circuit (8).

The metal of the contacts must be reduced to a gas by boiling before it is available for any considerable ionization. The gases absorbed by the metal are available for ionization, however, as soon as they have been driven out by the application of heat or under the influence of a sufficiently high electric potential. Heat and an electrical potential are both present when the contacts of an oil circuit breaker part in service, and ionization and a subsequent arc between the opening contacts are inevitable. The suppression of this arc under the high potentials and with the great concentrations of power now in everyday use by the large power companies has brought forth several types of oil circuit breakers, each with its own theory of operation. They will be discussed in detail in another part of this text.

CIRCUIT-BREAKER ACTION

The interruption of a high-voltage circuit by an oil circuit breaker is accomplished primarily by separating the contacts. The suppression of the arc and reduction of current flow are a secondary function but present the real problem in high-voltage circuit-breaker design. Nearly all oil circuit breakers, and especially those in use at high voltage, are in service on alternating-current systems wherein the current and voltage pass through zero once every half cycle. It is this fact alone which makes the high-tension oil circuit breaker a practical possibility as a piece of electrical equipment.

The circuit breaker itself, except to a limited extent, as will be discussed later, has no control over the various factors which affect its operation, since circuit connections, and connected equipment, determine the amount of current, the voltage, the power factor, and the recovery voltage that it will be called upon to handle in interrupting a circuit.

In action, the contacts part while carrying current. An arc is formed and develops until large enough to carry all of the current which the circuit is capable of supplying, while the contacts are moving a relatively short distance com-

pared to the total opening of the switch. The current decays to zero, and some cooling takes place, and the current builds up in the opposite direction. The conducting gases require a certain voltage, usually low compared to the circuit voltage, to ionize the heated gases and reestablish the arc.

Each succeeding cycle requires a higher voltage to strike through between electrodes and reestablish the arc. Usually, with the contact speeds common to present-day oil circuit breakers, several cycles pass before any voltage is apparent across the arc with the usual voltage-measuring equipment. In other words, the arc voltage is only a very small percentage of the open-circuit voltage. Eventually, the arc is not reestablished until an appreciable part of open-circuit voltage is available across the opening between contacts and there is an appreciable lapse of time from the zero point of each half cycle during which no current flows. This time lag increases until finally full open-circuit voltage is sustained across the gap between contacts without the formation of an arc, and the circuit has, thus, been completely interrupted.

The foregoing analysis of oil circuit breaker action has been simple and straightforward, but it is rarely that a record of such a uniform sequence can be obtained. Various factors tend to modify the action and alter the process.

FACTORS INFLUENCING OIL CIRCUIT BREAKER OPERATION

The factors which modify the action of an oil circuit breaker will be considered separately in accordance with the following outline:

1. Factors depending upon oil circuit breaker design:
   a. Arc suppression:
      (1) Effect of contact speed.
      (2) Means of increasing contact speed:
         (*a*) Accelerating springs.
         (*b*) Quick-break contacts.
         (*c*) Explosion-chamber contacts.
         (*d*) Multibreak contacts.

(3) Introduction of series reactance and resistance as contacts part.

b. Absorption of the energy of the arc:
(1) Volume of oil.
(2) Head of oil above contacts.
(3) Ventilation.

c. Possibility of maintenance in service:
(1) Maintenance of insulation.
(2) Maintenance of operating parts.

2. Factors depending upon circuit characteristics:
a. The total kilovolt-ampere reactance and transient characteristics of all of the connected synchronous equipment.
b. The number and characteristics of the several circuits connected to the oil circuit breaker.
c. The character of the short circuit, *i.e.*, resistance or reactance.
d. Phase connection of the short circuit, *i.e.*, single phase, three phase, or phase to ground.
e. Phase relations at instant of short circuit, *i.e.*, point on voltage wave.
f. Time from instant of short circuit to complete interruption.
g. Nature of interruption.

The seven items listed under group 2 may be redivided to cover recovery voltage, resonance, load characteristics, etc., and are frequently so classified (9). In connection with studies of system stability, they are all considered as transient characteristics. In considering the oil circuit breaker, it is desirable to use the terms employed in system-stability studies, for the reason that both problems are closely allied. Were it not for the fact that system stability is dependent upon proper oil circuit breaker operation, almost any oil circuit breaker would suffice if it could be depended upon ultimately to open the circuit safely. Speed of oil circuit breaker operation is, however, essential to the maintenance of system stability, and this means the interruption of heavy currents before the current has had an opportunity to drop and, consequently, imposes severe duties upon the breakers involved in clearing the trouble.

CHAPTER V

FACTORS DEPENDING UPON BREAKER DESIGN

ARC SUPPRESSION

Effect of Contact Speed on Arc Suppression.

It was at one time the opinion of transmission engineers that a too rapid interruption of the circuit of a high-tension transmission line was undesirable. Present-day practice has proved the opposite to be true, and it is highly desirable to isolate trouble in the shortest possible space of time. This requires fast breaker operation and imposes severe duty. The problem then becomes one of designing a breaker which will meet its requirements safely and open the circuit without injury to itself, to connected apparatus, or to nearby equipment.

The one thing in the circuit breaker which is the source of all trouble is the arc which follows the separating of the contacts. This fact is obvious, for, without the arc, there would be no circuit-breaker problem. The arc causes burning of contacts and generates gases which, in time, may build up pressures sufficiently high to rupture the tank. All of this represents energy but, unfortunately for the securing of comparative data, in a form extremely difficult to measure. The usual means of comparison of circuit breakers is the measurement of the volume of gas generated and the pressure produced in the tank. This is not an accurate measurement of the energy of the arc unless time is considered and does not give a true basis for the comparison of different breakers. A far more accurate basis for the comparison of breaker performance would be a measurement of the kilowatt-seconds of energy developed in the

arc. So far, no accurate method for this measurement has been devised.

In examining typical oscillograms of the interruption of a high-voltage circuit by an oil circuit breaker, it will be noted that the curves show no appreciable voltage across the arc for the first three or four cycles. A difference of potential must exist, or current would not flow. It is, however, a very small voltage compared to the phase-to-phase voltage of the transmission line. The arc voltage builds up in an irregular manner as the contacts continue the opening stroke, until, finally, the arc is extinguished and full-circuit voltage is sustained across the open contacts. This means that, in the case of measurements on a 100-kv. breaker, the voltmeter element of the measuring device must be capable of accurately recording voltages over the full range, from a few hundred volts or less to full-line potential of 100,000 volts. The range is too great for accuracy, and practically no deflection can be seen on the record for several half cycles. Under these conditions, the obtaining of wattage readings is at present almost impossible, yet it is that reading which is essential to direct comparison of circuit-breaker performance.

About the only method of comparison of breaker performance thus far used has been the measurement of gas generated together with observations as to the general breaker operation, *i.e.*, the pressures in the tank, whether oil or flame were emitted, the burning of contacts, and other visual evidences of distress. These give a rather indefinite comparison and have caused different conclusions to be reached by different designers.

In 1915, an engineer of the General Electric Company said (10):

> As a result of thousands of tests...we have found that doubling the velocity with which the contacts of a particular oil circuit breaker part increases its circuit-interrupting capacity about 30 per cent, while doubling the series breaks will increase the circuit-interrupting capacity about 70 per cent.

Stating the foregoing in another way, let us consider a two-break switch with the contacts parting at a speed of 5 ft. per second. The speed of arc break is then 2 × 5, or 10 ft. per second. Doubling the speed of break will give 20 ft. per second. If the original breaker had had double the number of breaks, or four, the speed of break would have been 4 × 5, or 20, ft. per second. According to the statement referred to above, 20 ft. per second with a two-break switch is not so effective in increasing interrupting capacity as 20 ft. per second, with a four-break switch. The conclusion seems logical, inasmuch as the arc is broken up into smaller sections in the latter case and is more easily suppressed.

Another engineer of the General Electric Company stated, in 1924, that (11):

> The interrupting capacity of a breaker depends upon the speed of break, but one cannot say, the higher the speed the greater the interrupting capacity, in every case. The interrupting capacity of a breaker depends not only on the quantity of gas generated but also upon the speed of generation, and it may well be that a given breaker, if operated at a higher speed, will have a lesser interrupting capacity.

One of the oil circuit breaker design engineers of the Westinghouse Company makes the following observations (12):

> The magnetic blowout effect is of negligible importance on high-voltage breakers where the current to be interrupted is only a few thousand amperes. On the other hand, the use of high-speed breaks on low-voltage breakers, where the interrupting current is large, would be entirely superfluous. The best results are obtained when the most effective principle for a particular range of circuit-breaker sizes and capacity is limited in its use to such sizes. . . .
>
> The increased efficiency of the magnetic blowout with increasing currents is shown in Fig. 22, in which ordinates are r.m.s. currents and abscissas are cycles of arcing on a 13,200-volt, 25-cycle circuit. It is evident that the curve becomes asymptotic at one-half cycle. This curve represents the data from a large number of tests on several sizes of breakers and various oil conditions and illustrates the dependability and regularity of operation under

these conditions of breakers using this principle [magnetic blowout].

On the other hand, for high-voltage breakers in which the magnetic blowout effect is inherently small, some device must be resorted to to prevent building up between the contacts of a pillar of arc gas, which may result in an unnecessary long period of arcing. For this purpose, high-speed breaks are particularly useful. Anyone who has had the experience of opening an ordinary knife switch will realize the difference that high-speed contacts make on

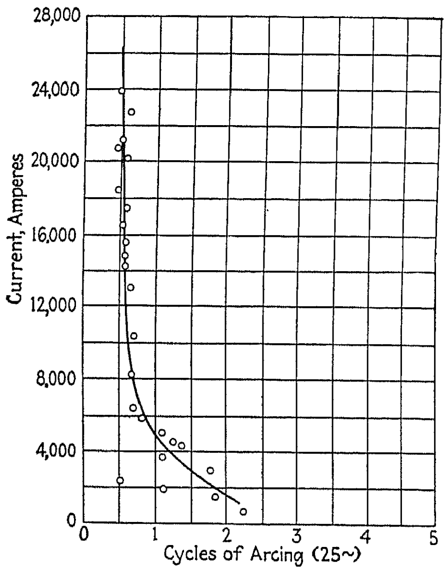


FIG. 22.—Duration of arcing with magnetic blowout for arc suppression.

arc duration and the amount of burning on the contact parts. . . . The time for a given break with high-speed contacts is approximately one-third that required for the same displacement with ordinary break, and this ratio holds closely over a large range of voltage classes.

There seems to be no doubt but that high contact speed is desirable and results in increasing the interrupting capacity of an oil circuit breaker. What seems to be in doubt is the degree in which higher contact speeds increase interrupting capacity, and until more accurate methods of

measuring kilowatt-seconds of arc energy are devised, no definite proof can be offered.

Means of Increasing Contact Speed.

The advantage of an accelerated contact speed was recognized before the first 60-kv. oil circuit breaker was built, and two types of air switches with accelerated breaks are illustrated in Figs. 9 and 10 in the historical section. The first oil circuit breakers depended upon gravity or relatively slow operating mechanisms to open the contacts, and it was thought that the oil would have sufficient quenching effect to suppress the arc in ample time. This soon proved to be an error, and designers set to work to devise ways to accelerate the parting of the contacts of oil circuit breakers.

In general, these designs fall into four distinct methods of achieving a quicker break: first, the introduction of accelerating springs which store energy during the closing stroke of the breaker to be released at the instant of tripping; second, the addition to the main contacts of secondary quick-break contacts; third, enclosing the main contacts in an explosion chamber, which acts in the nature of an expulsion fuse to force the contacts apart; and, fourth, the multibreak contacts wherein the circuit is simultaneously interrupted at several points.

Accelerating Springs.—The first type of accelerating mechanism which employs a spring to store energy during the closing stroke is to be found in practically all of the present-day high-voltage oil circuit breakers. All of the vertical-break breakers depend upon gravity to complete the opening stroke, and this accelerating spring is necessary to impart a reasonable speed to the contacts at the beginning of the break. From a system-operating standpoint, this method is not desirable.

The operating time of an oil circuit breaker should be kept at a minimum. If part of the energy applied to the

closing of the breaker is diverted to the stressing of a spring to be used in connection with the opening of the breaker, the breaker must entirely complete its closing stroke if the spring is to be fully stressed and useful for accelerated opening. This seriously interferes with the trip-free action of the breaker or, in other words, makes the breaker much less valuable for line testing where it may be closed in on a short circuit and be instantly tripped out again. Also, the maximum closing energy is required at the time of completing the stroke when the contacts are finally forced home, and no closing energy should be diverted to another purpose. At its best, the accelerating spring action is not a full solution of the quick-break problem, because the force of the spring does not continue throughout the complete opening stroke but lasts only until the contacts have parted and completed a portion of the downward stroke. Gravity then completes the opening of the breaker.

Quick-break Contacts.—In addition to the accelerating springs, a number of oil circuit breakers are also equipped with secondary quick-break contacts on the main contacts. These serve a double purpose. They relieve the main contacts of actual current-interrupting duties by forming a shunt path, which opens the circuit after the main contacts have parted and prevents burning and pitting of the main contacts. Secondly, they have a snap action which makes a quick break. By holding in after the mechanism of the switch has started its opening stroke and then snapping open due to the action of relatively light springs, a very much quicker break is accomplished. Here, again, energy is taken from the main operating mechanism and stored in a spring for future use, and the same objections hold true. The switch trips and begins to open. The quick-break contacts hold in against a spring which is being stressed until sufficient tension is applied to free the contacts of the quick-break switch. A decided deceleration due to this holding action by the quick breaks can be measured, but with the best designs of modern oil circuit breakers the total

speed of break is increased to approximately three times the main contact speed without the quick-break contacts. An example of a gravity-opened oil circuit breaker using the quick-break contacts is the present Westinghouse breaker, described under Modern Oil Circuit breakers and illustrated in Figs. 32 and 33.

Explosion Chambers.—The explosion-chamber type of accelerated-break contacts is a product of the General Electric Company, who have been staunch advocates of this type of breaker for high interrupting duties for a number of years. About 1904, the type H breaker built by the General Electric Company, described in the historical part of this text and illustrated in Figs. 4 and 5, proved inadequate for the circuit-interrupting duties imposed by the growing demands of the additions to the generating equipment of the various operating companies. In order to increase its rupturing capacity, wooden baffles were placed inside the tanks to minimize oil throwing when interrupting heavy currents. This was the beginning of the explosion-chamber breakers of the type now offered by the General Electric Company and described in the part devoted to modern breakers.

The action of the explosion chamber is due to the pressure built up within the chamber by the gas generated by the arc. This acts on the bayonet-contact rod, causing it to function as a piston, and increases the speed of break. The characteristics of the explosion chamber are very similar to the effects obtained through the use of magnetic blowout, as far as current rupture is concerned, in that the speed of break increases with increased current interrupted. A comparison of the action of explosion-chamber contacts with that of plain-break contacts was presented by an engineer of the General Electric Company in a discussion of several papers on oil circuit breakers presented at a convention of the A. I. E. E. in 1924. He says (14):

A series of tests was made upon plain-break and explosion-chamber breakers, and operating in the same plant, with the same

mechanism by the same generator, under the same circuit connections and load. Broadly speaking, we found that in that particular test the maximum amount of gas with the explosion chamber at 1,200 amp., at 63,000 volts, was about one-third of the minimum amount with the plain break; that the maximum amount with the explosion chamber was about one-tenth of the maximum amount with the plain break. With increased duty the explosion-chamber breaker has a speed increase due to the increased pressure in the explosion chamber. The plain breaker shows very little change in speed. Whatever change there will be, however, in the plain-break breaker is a decrease in speed, rather than an increase. That comes from the increased pressure in the tank acting upon the rod passing through the tank and, also, upon other factors which all tend to decrease the speed of operation. The rod passing through is acting as a piston, and the force of that piston is acting opposite to the force of acceleration given by the spring, and this tends to slow up the breaker.

A series of tests was recently made by the A. E. G. Company of Germany to determine arc duration. In a two-break explosion-chamber breaker at 80,000 volts, the longest arc duration was 9 half cycles on a 50-cycle circuit; at 70,000 volts, the arc duration was about 7 half cycles. In the plain-break breaker, with six breaks in series, the maximum arc duration at about 65,000 volts was 25 half cycles.

In a paper which he presented at the above-mentioned meeting, the same engineer says (15):

In order to be efficient, the explosion-chamber breaker must operate at large pressure in the chamber; hence, a breaker designed to have an interrupting capacity of 3,850 amp. at 44,000 volts does not begin to show its remarkable current-interrupting capacity until approximately the safe limit of the plain-break contact in the same tank is reached. Up to that point, it functions largely as a plain-break breaker and is given the break distance required by such a breaker. From then on, the gas pressure acting on the rod increases, the breaker speed increases, the arc becomes shorter, and at maximum rating the arc duration is a minimum. The designer has full control of these characteristics and the breaker as a whole can be largely designed to meet any particular condition.

Dr. Kesselring, speaking before the Elektrotechnischer Verein on Dec. 14, 1926, stated, in part, that as long as the circuit interruption, even without explosion chambers, took

place in one or two half periods, the explosion chamber worked less satisfactorily, because a higher pressure existed in the explosion chamber, causing an increased arc voltage and increased vapor formation. If the power to be interrupted was increased, however, the time for interruption increased with a breaker without explosion chambers, while it remained practically constant with explosion chambers. In this case, the breaker with explosion chambers, in general, dissipates less energy, because the shorter interrupting time decreases the total energy absorbed in the breaker.

If the current interrupted is of such a magnitude that it will cause the arc to follow the bayonet rod out of the explosion chamber, conditions are practically reversed, because the interrupting times are almost the same and the explosion chamber is submitted to less favorable conditions during the first part of the interruption. It, therefore, follows that explosion chambers should always be designed so that a continuance of the arc outside the explosion chamber cannot take place.

Further discussion of the action of the explosion-chamber type of contacts is set forth by an engineer of the General Electric Company in commenting on a paper presented at a convention of the A. I. E. E., in 1927, as follows (16):

> It is also a fact that the speed of operation of the explosion-chamber breaker is a maximum shortly after the end of the contact rod clears the throat bushing—that is, the speed is a maximum at the time of the long arc, and this means the smallest quantity of gas during that period. This should be compared with the breakers having the maximum spring tension and maximum speed during the early stages of arcing when the gas generated per unit of arc length is small. In one case, we have a maximum speed decreasing to a minimum; in the other case, we have a minimum speed increasing to a maximum.
>
> The quantity of gas generated at constant speed of contacts for a given arc duration varies approximately as the square of the speed, because the arc likewise varies directly as the speed.
>
> When the above facts are considered, it is easily seen why the explosion-chamber breaker produces such a small quantity of gas and why it has such a high interrupting capacity.

It is not clear to the writer why high speed of separation is necessary when interrupting line-charging current or load currents of small magnitude, because under these conditions the line should be fairly stable.

For heavy short circuits, however, high speed would be advantageous, and it is under these conditions that the explosion-chamber breaker is at its best, and its strong construction enables it to stand repeated interruptions without damage.

From the foregoing observations and opinions of engineers familiar with the explosion-chamber type of contacts, one may infer the reason why the explosion-chamber breakers enjoy a well-deserved reputation on moderate voltage, high current duty, and why, on the other hand, their use or suitability for application at high voltage with relatively low current duties has been questioned by some operating engineers.

With respect to the design of the explosion-chamber contacts, it was stated that "the breaker as a whole can be largely designed to meet any particular condition." In this statement may be found one of the fundamental objections to both the magnetic-blowout breaker and the explosion-chamber breaker for high-voltage service. They can be made to function for a given condition, which, in each case, requires a relatively high current of the order of 3,000 amp. or above, and do not function for all conditions, especially when interrupting normal-load currents of the order of the rated continuous current-carrying capacity of the breaker. In another part of this text, the necessity for interrupting low values of current will be considered, and experimental evidence produced to show that, ampere for ampere, it is from fifteen to twenty times as difficult to rupture line-charging currents as it is to interrupt an inductive short circuit at the generator terminals.

Multiple Breaks.—The multiple-break oil circuit breaker has come generally to be accepted as a breaker having more than two breaks in series per pole. The first makers of practical oil circuit breakers for voltages in excess of 20,000 included in their list multiple-break breakers having four

breaks per pole. These have been described in the historical section of this text. The advantages claimed for this type of breaker are

1. The speed of total break can be increased tremendously.
2. The arcs are broken up into small sections and are easier to suppress.
3. The total time of operation is reduced.

This last point is vital to operating companies. The principal function of the oil circuit breaker is to protect the transmission-system network and isolate trouble. Present-day practice demands that this be accomplished before the system is broken apart and out of synchronism, and, therefore, high-speed oil circuit breaker action is essential.

Four American manufacturers of oil circuit breakers are now offering multibreak breakers for high-voltage duty. They are the American Brown Boveri Company, the Condit Electrical Manufacturing Corporation, the Kelman Electric Manufacturing Company, and the Pacific Electric Manufacturing Corporation. Each company offers breakers distinctly different from the others, and descriptions of the several makes will be found in the part devoted to Modern High-voltage Oil Circuit Breakers.

Multibreak oil circuit breakers have been the subject of many papers and discussions, and much has been said and written concerning them. In 1915, an engineer presented a paper before the A. I. E. E., in which he stated (17):

> An increased number of breaks in series, entirely neglecting method of accomplishment, would seem desirable, as the simultaneous opening of several breaks will accomplish the intervention of a given oil distance more rapidly than will a smaller number of breaks, assuming that the rate of contact separation remains roughly the same for both. With the increased oil distance, recovery after the first zero point is less likely. On the other hand, it is apparent that with the drop across each arc practically constant, the energy dissipated in the multibreak unit during the first half cycle will be roughly proportional to the number of breaks and greater than the fewer breaks.

In discussing the paper just quoted, an engineer of the General Electric Company said (18):

> We have found that doubling the velocity with which the contacts of a particular oil circuit breaker part increases its circuit-interrupting capacity about 30 per cent, while doubling the number of series breaks will increase the circuit-interrupting capacity about 70 per cent. . . . The oil circuit breaker is a device for dissipating the stored electromagnetic energy of a circuit. It performs this function by converting this energy principally into heat, which appears in the form of an arc at the oil circuit breaker contacts. If this arc is distributed between a large number of contacts, a greater rate of energy dissipation may be acquired and the circuit-interrupting capacity of the oil circuit breaker increased. If, on the other hand, the velocity with which the contacts of the oil circuit breaker part is increased, the time duration of the arc may be diminished, but since the number of arcs is not increased, the rate of dissipation is not nearly so rapidly increased, and, consequently, the circuit-interrupting capacity of the breaker is not nearly so high.

The vice president and chief engineer of one of the large American power companies states that he has on his system two-break breakers of one manufacturing company which have a break much more than twice the length of break on other four-break breakers. In his opinion, the two-break breakers never have given, and it is not possible for them to give, the service the four-break breakers give (19). It may be noted in passing that this power company is now using ten-break oil circuit breakers built to its own design by one of the large manufacturing companies.

In a discussion of European oil circuit breaker design, a professor of electrical engineering from Cornell University had the following to say regarding multibreak contacts (20):

> By dividing up the arcing distance, less energy is released, and since the gas is produced at several places throughout the oil volume, the latter is, therefore, much more quickly cooled. Moreover, the arc can be much more easily controlled and, therefore, several dielectric problems overcome without a complicated design. As it is realized that 100,000 volts require an arcing distance of over 70 in., the foregoing fact would be greatly appreciated in the design of high-voltage breakers.

A series of tests on oil circuit breakers was made at the request of the Swiss Commission of Railways, and one of the conclusions resulting from the tests is set forth by M. G. Bruehlmann in an article abstracting the report as follows (21):

> The breaking process is improved by increasing the number of breaking points. By such an arrangement a considerable reduction in the length of arc is obtained, which means lower arcing energy.

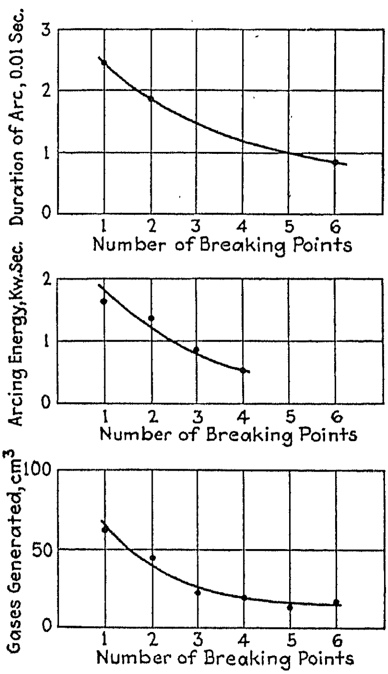


FIG. 23.—Relation of arc duration, arc energy, and gas generated to the number of breaks.

The curves in Fig. 23 show the relative duration of arc, arc energy, and gas generated with varying numbers of breaks in series as determined from the Swiss commission's tests.

Summary of Effects of Contact Speed in Arc Suppression.

From the foregoing, it is at once evident that the advantage of increased contact speed is realized but that the best method of achieving the increased speed is in doubt. Accelerating springs are only slightly effective in that they do not act throughout the full stroke of the breaker and have a detrimental effect in slowing down the circuit-breaker action. Quick-break contacts will increase the speed of break about three times over that of plain-break contacts, but here, again, there is a delayed action due to the necessity of storing energy in the spring for subsequent release. Such contacts, therefore, relieve the breaker of duty at the expense of the system on which that breaker operates, since the system disturbance continues during the time taken to actuate the quick-break mechanisms.

The explosion-chamber type of breaker contact takes the place of accelerating springs and offers no resistance to closing. The explosion-chamber contacts, however, have the characteristics of the magnetic blowout and find their greatest usefulness with heavy-current duty. They are not much different from a plain-break breaker with accelerating springs when opening small currents. This is a distinct disadvantage, as it is frequently necessary on long high-voltage transmission lines to interrupt a charging current which is smaller than the rated interrupting current of the breaker. Due to conditions discussed later under the part on Tests, this charging current is many times more difficult to interrupt than a power current, and imposes a heavy arc suppressing requirement on the breaker.

Finally, the multibreak-contact arrangement seems to have none of the disadvantages of the three previous methods of speeding up the break but, on the contrary, has several distinct advantages. The speed is increased in direct proportion to the increase in number of breaks in series for a given switch operator and the arc is broken up into small sections which are more easily controlled. Accord-

ing to some operating engineers, the multibreak switch, when equipped with a fast and powerful operator, is the most desirable type of high-voltage oil circuit breaker thus far offered by the manufacturers.

Proof of this opinion cannot be demonstrated save by actual trial on operating systems, but there is an increasing tendency toward multibreak combinations. One large operating company has actually designed ten-break multi-contact breakers in its own engineering department and had them fabricated by one of the large manufacturing companies. The operating head of the company declares that these breakers have given better service than any standard breakers at present in service on the 132-kv. system of his company. In connection with speed of break and arc length, one important point is frequently overlooked: The energy in the arc and, therefore, the duty on the breaker, is the product of the voltage across the arc and the current in the arc in phase with it. An arc acts as a resistance for a given current and has very little inductance, and, since the current is controlled by the connected apparatus, the resistance increases in proportion to the length of arc. This has been repeatedly checked by oscillographic records. In other words, the resistance of the arc is a function of the arc length and, for a considerable portion of the curve of arc resistance against arc length, is in direct ratio. In an oil circuit breaker, the length of the arc, and, consequently, the arc resistance, is a function of time, since the length of the arc increases as the breaker contacts part up to the time of final interruption. This may be set down as an equation similar in form to $R_a = kt$, in which R_a is the resistance of the arc, t the seconds duration of the arc, and k a constant. The voltage across the arc will then be $E_a = I_aR_a = I_akt$, and the power in the arc will be represented by the equation $E_aI_a = I_a^2R_a = I_a^2kt$. The work done, and, consequently, the energy absorbed by the breaker, which requires t sec. to interrupt the arc, will be

$$E_aI_at = I_a^2kt^2 = \text{kw.-sec.},$$

from which it is seen that the severity of the duty imposed on an oil circuit breaker varies as the *square* of the time of arcing and not in direct ratio, as is frequently assumed. Increasing the speed of break may increase the total length of arc, but its increased length is offset by a decrease in kilowatt-seconds of energy to be dissipated.

The foregoing statement is strictly true only if the resistance of the arc is proportional to its length and the speed of contact movement is uniform. The curve of kilowatt-seconds plotted against speed of break tends to become asymptotic to the speed axis at high speeds and to the kilowatt-seconds axis at low speeds.

In actual practice, the test values of kilowatt-seconds do not follow the values of either the length of arc or the square of the time of arcing except in small breakers tested directly on a generator, because on an operating system the recovery voltage may be resonant or partly resonant and, thus, affect the arc energy. Such data as are available from tests indicate that the variation in kilowatt-seconds follows a law in which the exponential function of time lies somewhere between 1.5 and 1.7 rather than 2.

The energy absorbed by an oil circuit breaker is manifested principally as heat,[1] which, in turn, is mostly utilized in the generation of gas, and, for this reason, the measurement of gas generated has been one of the most frequently used methods for the comparison of oil circuit breaker performances. There is, however, a considerable variation in the results obtained from experiments made to determine the amount of gas generated per kilowatt-second, values varying from

46.5 cm.^{3} per kilowatt-second, determined by Bauer (22);
50 cm.^{3} per kilowatt-second, determined by Bruehlmann (23);
60 cm.^{3} per kilowatt-second, determined by Kesselring (24),

for moderate sizes of low-voltage breakers on up to still higher values on high-voltage systems.

[1] See field tests, p. 247.

Formulæ for determining the interrupting capacity of oil circuit breakers, based entirely on breaker dimensions, cannot apply to all conditions, since only one of three variables entering into the operation of the breaker as a current-interrupting device is within control of the breaker itself. This is contact speed. The current in the arc and the voltage across the arc are controlled by the connected circuit, and the kilowatt-seconds of energy dissipated may vary widely for the same bus voltage and short-circuit current even on the same transmission network. It is only since wattmeter elements have been made available for use in oscillographs that an adequate study of the energy liberated in an oil circuit breaker could be made in the field. Even then, exceptional care and attention must be given to instrument transformers and connections if reliable results are to be recorded. It is this lack of accurate measurement of kilowatt-seconds of arc energy which accounts for many of the inconsistent test results which have been published and, also, accounts for the lack of definite comparison of breaker performance.

The discussion of the effects of contact speed on oil circuit breaker operation would not be complete without mention of the physical action of the moving contact parts through the oil. It has frequently been thought that too rapid movement would cause "cavitation" or the formation of a vacuum in the wake of the rapidly moving part, which would persist an appreciable time before the force of gravity could fill the void. The subject has been studied by a French engineer, who has devoted considerable time to the theory of oil circuit breaker operation, and a liberal translation of a portion of a paper on the subject follows (25):

> But before leaving the examination of this question of velocities, we shall consider another fantastic conception, which has been opposed to the employment of large velocities, namely, cavitation.
>
> When a solid is rapidly displaced in a fluid, there is produced behind the solid a depression which is larger as the velocity is larger.

Liquids being very slightly elastic, there cannot be a question of a depression but only of a vacuum. But the oil precipitates itself into this vacuum with a velocity depending upon the pressure existing in the medium.

If we consider a cylindrical contact of radius R being displaced in the oil with a velocity v, the volume swept in the time t by its upper base is

$$\pi R^2 vt.$$

The oil tends to precipitate itself in the vacuum left behind the contact with the velocity

$$v' = 2gh',$$

h' being the height of the column of oil which is equivalent to the pressure of the medium.

One may admit that this jet of oil is directed along the axis of displacement of contact. Its section will be, then,

$$\pi R^2,$$

and its quantity in unit time,

$$\pi R v'.$$

A vacuum can evidently not be produced if one has

$$\pi R^2 v' < \text{ or } = \pi R^2 v$$

or

$$v' < \text{ or } = v.$$

In supposing that h' corresponds to the atmospheric pressure, we have $h' = 12$ m/s approximately.

$$v' = 2gh = 15 \text{ m. per second.}$$

It is thus necessary that the contact have a velocity at least $15^m/_s$ in order that cavitation may be produced, even in supposing that the oil remains at atmospheric pressure during the interruption.

However, the velocities of this order cannot be attained in practice during the short duration of the interruption.

In addition, the pressure of the oil in the neighborhood of the contact is about 5 kg. per square centimeter at least, and under these conditions the velocities which must be obtained by the contact would be more than 60 m. per second to cause cavitation.

The fear of cavitation thus does not oppose the use of the largest velocities that one may attain practically and which are

becoming indispensable in order to obtain the rapid rupture of arcs at very high voltages.

The foregoing discussion of contact speeds and methods of increasing contact speeds has been interspersed with liberal quotations from the leaders in American oil circuit breaker design. Each designer follows and attempts to justify certain principles of design sponsored by the manufacturer he represents.

The opinions given are, for the most part, generalizations drawn from specific data on a specific type and often on a specific oil circuit breaker. Such generalizations are a rather prevalent and dangerous practice in the industry. This is particularly true when comparing test data. It is quite evident that the statement, quoted on page 50, that breakers, other than the explosion-chamber type, will slow up due to the pressure acting against the motion of the contacts when interrupting heavy currents, applies to a specific construction employing a vertical downward break and cannot apply to breakers employing the horizontal break, two types of which are described in the part devoted to modern breakers. Many similar examples could be cited to show apparent contradictions or inconsistencies. The answer is that the various contributing factors often were different and the data compared were not properly comparable.

The greater portion of tests so far made on operating networks has been sales demonstrations the net result of which has been to create a widespread distrust of high-tension oil circuit breakers in general, so far as the operating companies have expressed themselves. That this distrust is not confined to the users of oil circuit breakers may be inferred from the withdrawal of all rupturing-capacity guarantees from the present sales contracts of the manufacturers. The indictment that the operating companies do not know what they want in oil circuit breakers is a true one, but it is equally true that it is the business of the manufacturer to find out what the buyer needs and offer it for sale. A satisfied customer is one who purchases the product

he needs at the price he can afford to pay, and a good sales organization should see that the purchaser gets what he needs and nothing else. The business of the operating companies is to generate and sell kilowatt-hours, and it is not a part of their business to design oil circuit breakers. All they can do is to specify their requirements, and in the absence of any tests and without guarantees they have no means of knowing that the specifications have been met. In the light of conflicting and unsupported claims as to rupturing capacities, the operating companies have been forced to conduct expensive and costly tests for their own information. Quoting from an operating-company engineer, who was discussing a paper on oil circuit breakers presented at a convention of the A. I. E. E. (26):

> I, again, am in entire agreement with the authors in that the only way for an operating company to know today as to whether the breakers that it is buying or that it contemplates buying will or will not perform satisfactorily, on its system, is to test them. Some day, breaker development will have reached the point where this will not be necessary, but it does seem necessary today.

Some of these tests will be discussed in another part of this text.

This text is concerned only with high-voltage oil circuit breakers, that is, breakers for use at voltages of 60 kv. and above. No attempt has been made to consider breakers for lower-voltage duties, for their design and application are a problem distinctively different from that encountered on the high-voltage equipment. High current values are the usual order of things in low-voltage installations, and for this duty full advantage can be taken of the magnetic-blowout effects and the accelerated action of explosion-chamber contacts. The opposite is true with high-voltage breakers. Currents exceeding 5,000 amp. are the exception rather than the rule in routine switching, and even fault currents rarely exceed that value. Consequently, magnetic-blowout effects are not of sufficient value to be of material assistance in arc suppression. Increased spacings, due to

the insulation required by the higher voltages, still further reduce the effect of the magnetic fields, and this type of breaker is not adapted to high-voltage service. The explosion-chamber type of breaker suffers similarly, due to the less explosive action of the lower currents, but the effect is not so pronounced as with the magnetic-blowout type.

It is extremely difficult to make direct comparisons of commercial breakers. Extrapolated curves derived from tests at lower voltages fail to take into account the lessened magnetic effects of the lower currents, and such curves must be used with extreme caution. In some cases, manufacturers have conducted tests on breakers of a type offered by competitors, but unless these tests were made on the exact product of the competitor, results are of slight value. It will not suffice, for instance, to set up the contact mechanism in a tank other than the one for which it was designed. Results are quite likely to be misleading, and incorrect conclusions drawn. Finally, factory testing equipment cannot exactly reproduce actual service conditions, and there is a considerable variation in the testing facilities available at the factories of the different manufacturers. To be at all comparable, tests must all be conducted at the same place, under the same conditions, and on the exact equipment offered by each manufacturer. Obviously, if one manufacturer tests a competitor's equipment along with his own, he cannot publish the results of these tests. The results would be criticized and suspicion cast on the integrity of the tests. As a result of this condition, most operating engineers have entirely discounted factory tests as a means of comparing oil circuit breaker performance and rely only on actual performance in service for comparative data.

There is a growing conviction that the kilovolt-amperes which a breaker handles is the product of the current in the arc and the voltage across the arc at any instant and that this is entirely dependent upon circuit conditions. The breaker has no control over either the current or the voltage and must accept what the connected circuit imposes.

An engineer of the General Electric Company states that (27):

> The interruption of a given number of volt-amperes by the breaker—for example, 100,000 kva.—does not necessarily impose the same stresses as result from the interruption of the same kilovolt-ampere at other times at the same point on the system, at other points on the system, or on different systems. In other words, volt-amperes are not equally "hot" at all times and places, due to a number of causes. It seems probable that this difference in the difficulty of interruption depends largely upon the magnitude of the voltage "kick" at the end of each half wave of arc and upon the speed at which each half wave of this transient voltage is built up. The need for making many tests on a device and making them under the most severe operating conditions is clearly indicated. . . .
>
> To give a concrete illustration of what may be expected, I shall cite one particular test in which the length of arc drawn in the same breaker operating with the same kind of oil, at the same speed, on the same system—*but a different part thereof*—at the same voltage and current interrupted consistently gave an arc nearly three times as long in one case as obtained in the other. In one case, the breaker was safe; in the other, it was severely stressed, and, if the break distance had not been large, it would have blown up.

The speed of contact movement has been one of the most controversial subjects entering into the discussion of oil circuit breaker performance. The designers have, in general, opposed high speed in an effort to favor breaker operation, while the operating engineers have urged high speeds in order to bring about the fastest possible clearing of system faults. The attitude of the operating-company engineers has been that the maintenance of service is of paramount importance and that oil circuit breakers should be designed with that end in view and not with any idea of making the duty on the breaker easier at the expense of system stability. As has been previously pointed out, the only one of three factors entering into the interruption of the arc which is within the control of the oil circuit breaker designer is the speed of break, and there is no question but

that the breaker must be so designed that the necessary separation between contacts to prevent reestablishment of the arc should be achieved in the minimum time.

Series Reactance and Resistance to Limit Current.

The flow of current in an electric circuit is a function of the resistance and reactance of the circuit, current decreasing with increased resistance or reactance when the voltage is maintained constant. Advantage has been taken of this fact in the design of some circuit-interrupting equipment. One of the earliest important installations of switches using resistance to limit the flow of current before the final interruption is to be found in the 5,000-hp., 2,300-volt switches used by the Niagara Falls Power Company and illustrated in Fig. 1 in the historical part of this text. In opening the circuit, this switch first opened a pair of contacts which normally shunted out a resistance, thereby inserting resistance in the circuit and reducing the current flow, which, in turn, relieved the duty on the contacts making the final break.

Intermittently since that time, advocates of multibreak circuit breakers have used various forms of resistance or reactance to assist in reducing the current before final interruption. Several European manufacturers are now offering high-voltage breakers built on this principle, and brief mention of the product of a few typical representatives will be found in the chapter devoted to modern foreign oil circuit breakers.

On account of the size and cost of a resistance suitable for handling the currents which modern high-duty breakers are called upon to interrupt, it has been necessary to resort to reactances or a combination of reactance and resistance. Those circuit-breaker manufacturers using the two-break type of oil circuit breaker in its various forms advocate, build, and sell reactors to be placed in series with feeders supplied from a station bus where it is uneconomical or not

yet possible to install oil circuit breakers with sufficient interrupting capacity to be safe. There is no question as to the desirability, practicability, or necessity for series reactors in certain installations, and thousands are in use. Each one of the large electrical manufacturers recommends and sells all sizes of current-limiting reactors or resistors, from very small ones to be used in series with potential transformer fuses up to those suitable for handling many thousand kilovolt-amperes on large station busses.

The logical place for such reactances or resistances is across one pair of contacts of a multibreak oil circuit breaker, where they will be in the circuit only when needed to limit the current and where the losses inherent in the apparatus will not constitute a continuous energy charge against the generating equipment. The argument against such an arrangement is that it is not physically or economically possible to add such reactors to present-day oil circuit breakers. With this argument there is no disagreement, and they are not made a part of such oil circuit breaker installations.

Reactors are installed for the specific purpose of limiting the current flowing into a short circuit, in order that the interrupting duty on the circuit-opening equipment may be reduced. They affect the circuit conditions, and their effectiveness is solely dependent on their ability to change these circuit conditions. They are logically, and by right ought to be, considered a part of the circuit-interrupting equipment. Unfortunately, there are practically no data published in English on the performance of circuit breakers so equipped, and very little information is available from foreign publications. A report to the Swiss Commission of Railways, prepared by Dr. B. Bauer (28), and an article by G. Breuhlmann (29) constitute the best presentations of the subject thus far. Mr. Breuhlmann's article has been abstracted in the English edition of the *Brown Boveri Review* and appeared shortly after its appearance in the original French.

CHAPTER VI

FACTORS DEPENDING UPON BREAKER DESIGN

(Continued)

ABSORPTION OF THE ENERGY OF THE ARC

Volume of Oil.

ONE of the elements in oil circuit breaker design about which the least positive and reliable information is available and over which there has been much controversy is the amount and disposition of the oil. Fundamentally, the oil is put in the breaker tanks to secure increased insulation and reduce the dimensions of equipment. It was originally thought that the oil would be thoroughly effective in quenching the arc, but such is not the case. It has a very great cooling effect upon the arc, but, unfortunately, it cannot reach the contacts during arcing, because of the presence of the gas bubble surrounding the arc. The oil, therefore, loses its insulating value in so far as the voltage required to establish the arc after each half cycle is concerned. Due to the presence of the gas, the leakage insulation over the lower end of the bushings is, also, greatly reduced until the gas has percolated upward into the air space above the oil.

As the gas bubble expands, the carbon particles from the burned oil are directed along the lines of electrostatic force between the contacts and are eventually deposited on the surfaces where the lines of force terminate if the stress is high enough, or they fall to the bottom of the tank if it is not.

The question of the theoretically correct volume of oil to be used in a given breaker is one not subject to definite solution by any known formula. American designers attack the problem by the trial-and-error method on a full-sized test

breaker. One oil circuit breaker design engineer has ventured the opinion that (30) "Too much oil is as bad as too little. The correct quantity to use can be determined only by repeated tests at all loads up to the interrupting capacity of the breaker."

An attempt to establish a method for determining oil quantity by calculation was made by a French engineer who has devoted considerable time to the study of oil circuit breakers. His (31) theories were published, and a brief extract of the articles will illustrate the difficulties arising from an attempt to arrive at a mathematical solution of the problem. The author gives considerable specific data, which he has assumed as established fact but which American engineers have questioned. Specifically, he sets down a table for the length of an arc under oil for various voltages. Using values of arc length from this table in connection with the amount of oil which can be volatilized per kilowatt-second (also a quantity which is not yet definitely proved and which may be a variable amount, depending on conditions), he proceeds to develop a theory of the shape and size of the gas bubble formed as the contacts of the switch part. With the arc length and gas generated taken as known factors, he determines the diameter of the oil bubble and, therefrom, the diameter of the tank and the spacing of the electrodes. From the arc length he arrives at the necessary contact travel and the depth of the switch tank. The diameter and depth of the tank having been found, the volume of oil is determined.

The fallacy is that the design is based upon a hypothetical arc length fully admitted by American oil circuit breaker designers to be unknown for the higher voltages and variable depending upon circuit conditions. With a constant voltage the arc may remain of constant length with current variations of approximately 15 to 1, depending upon the external circuit characteristics, or it may vary greatly in length at constant voltage with the same range of current variation when the other characteristics influence the external circuit.

American oil circuit breaker designers have been reluctant to publish data on the subject of the volume of oil in a breaker. In general, the sizes of tanks on American breakers are determined by test, and new designs for higher voltages are based upon extrapolation of curves and tables determined by tests on lower-voltage oil circuit breakers.

Head of Oil above Contacts.

One of the greatest variations noted when comparing the breakers of different manufacturers is the height of the surface of the oil in the tank above the contacts. Many theories have been advanced which have resulted in the construction of breakers varying from the early Stanley type, shown in Fig. 15, with extremely light construction and small oil volume, to the opposite extreme of the so-called "battleship" or "bomb-proof" construction, containing a large volume of oil in a very heavy tank.

In investigating the effect of the head of oil in breaker performance, some idea of the physical phenomena of arc formation under oil is necessary. Various investigators have demonstrated that the first gas bubble generated when the contacts part is spherical in shape and that, due to the inertia of the surrounding oil and the speed of gas generation, relatively high pressures are developed very quickly. This results in impact waves of short duration but high intensity being transmitted to the walls of the tank. One investigator places the maximum pressure of gas generation as lying between 4 and 7 atmospheres (55 to 100 lb. per square inch), depending upon several conditions, among which is the rate at which energy is available (32). Secondary explosions of the inflammable gas and air mixture may, of course, produce much higher pressures.

As the spherical bubbles expand, the oil above the arc rises and compresses or forces the air out of the top of the breaker, depending upon whether or not the tank is vented. Oil-movement speeds from this cause have been recorded

at velocities varying from 3 to 15 ft. per second. It is this oil movement and air compression which act against the top of the switch tank to produce the familiar lift or jump of a breaker tank during heavy-duty interruptions. A set of sketches made from moving pictures is shown in Fig. 24 and illustrates the action, first, under light duties, then at rated duty for a plain-break breaker, and, finally, at rated duty on an explosion-chamber breaker. The action in each is much the same as far as oil lift is concerned. It will be noticed that the gas stream comes out of the explosion-

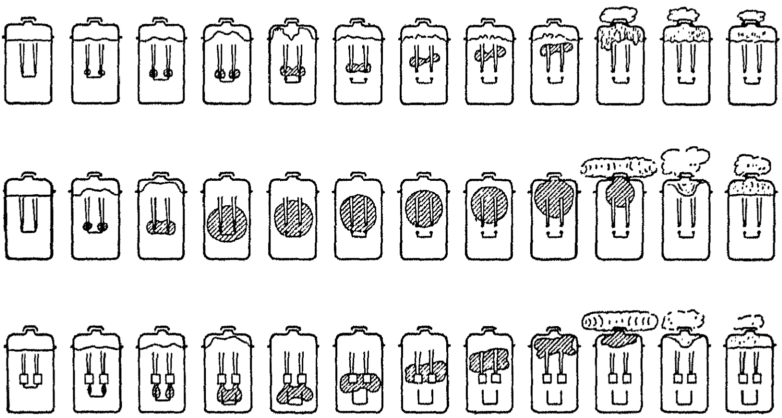


FIG. 24.—Gas generated and oil displacement in oil circuit breakers. Top: light duty; center: heavy duty; bottom: heavy-duty explosion pot.

chamber throat in the form of a column and then assumes the spherical shape. This, in a measure, accounts for the occasional tendency of the arc in explosion-chamber breakers to skip a cycle and then reform and, finally, clear. Pressures in the smaller explosion pots reach values as high as 16 atmospheres (224 lb. per square inch) (33).

No reliable data have thus far been offered which will enable a mathematical determination of the proper head of oil above the contacts. Instead, there seems to be some evidence pointing to a necessity for different heads for different types and for different duties in the same type.

Coupled with this is the volume of air permitted above the normal oil level, which varies in different types of breakers from one-seventh to one-quarter of the total volume of the tank. In action at maximum duty, this air reaches fairly high pressures in a relatively short time, when the whole oil column above the gas bubble acts as a compressor piston. At lower duties, the gas rises through the oil without any appreciable compression.

From such considerations it is evident that the head or height of oil over the contacts of an oil circuit breaker depends largely upon other features of the breaker design. Horizontal-break breakers secure a given break distance under the same static head of oil with less oil volume than vertical-break breakers. Multicontact breakers of the drop-bar type, such as Brown Boveri, usually have less total opening per break than two-contact breakers and, therefore, less oil volume for a given oil head.

From tests made for the Swiss Railways (34), the fact was definitely established that moderate pressures are detrimental to interrupting capacity. In the *Brown Boveri Catalogue* 782–*E*, dated May, 1923, the statement is made that "with a gage pressure of 7 kg. per square centimeter (99.56 lb. per square inch) the duration of the arc was 1.7 times; the arcing energy at least 5 times, and the volume of gas more than 20 times the corresponding values at atmospheric pressure." Data on very high pressures are not available.

The data available on high-voltage breakers at much higher interrupting duties consist mostly of observations made in explanation of features of the several tests made on the system of operating public utilities. These statements are very guarded and, in general, are restricted to bare statements of what was required to remedy defects or to the statement that the performance checked with the design.

Only a few of the many variables entering into the design of high-tension oil circuit breakers have been measured

in actual tests, and there is practically no conclusive information published anywhere on arc energy, amount of gas generated, etc. This scarcity of published data caused a French engineer to state:

> We regret the discretion which has kept the American manufacturers from publishing the results of their recent experiments, but if these experiments have been conclusive this discretion is doubtless explained by the embarrassment in which they would find themselves due to having equipped numerous installations with devices needlessly powerful and costly or, in other cases, dangerously insufficient.

The reaction of such lack of data and straightforwardness in presenting the results of tests and investigations is shown in the United States by the increasing demand for definite proof of an oil circuit breaker's ability to meet the claims as to its interrupting capacity as demonstrated by test and by the individual tests conducted by the electric-utility companies on their own systems. The results of these latter tests have, in general, been given considerable publicity, as is exemplified by the excellent paper by Sporn and St. Clair, describing tests conducted by the American Gas and Electric Company and presented at the winter convention of the A. I. E. E. in February, 1927. This paper is more fully discussed under the section devoted to tests on modern oil circuit breakers.

Venting of Oil Circuit Breaker Tanks.

In general, venting has been more vital on low-voltage than on high-voltage oil circuit breakers, due to the fact that clearances are less in low-voltage equipment and there are usually many breakers in a restricted space. A multiplicity of devices and means have been applied to low-voltage breakers safely to care for the gas generated when opening a circuit and to relieve the pressures inside the tank.

With increasing current-interrupting capacity demands on high-voltage breakers, it has become essential to provide

for the excessive pressures encountered. For this reason, high-duty breakers are now generally equipped with cast-steel or welded tops securely bolted in place and made oil tight by a gasket between tank and top. A vent is necessary to relieve the gases, and various forms are in use. The General Electric Company uses a separating chamber consisting of a tube filled with selected quartz pebbles, which separates the gases and oil vapors produced when the breaker interrupts a heavy current, allowing the gases to escape and returning the oil to the breaker tank. The Westinghouse Company makes use of a muffler somewhat similar to the muffler on the exhaust of a gasoline engine, and similar other devices have been added to their equipment by other makers of high-voltage oil circuit breakers.

These devices perform several functions. In addition to relieving the pressure generated inside the tank, they prevent the loss of oil, which is violently agitated by the action of the arc and hits the top and sides of the tank. They also permit normal breathing of the circuit-breaker tank, caused by the expansion and contraction of the oil with normal changes in air temperatures.

Certain European manufacturers fill the breaker tanks completely, with no air space at the top, and then, in order to allow for expansion, insert chambers or cups face down in the oil which trap air on the diving-bell principle. Performance data at very high voltages are not available on this type.

It seems unquestionably the best practice to vent oil circuit breaker tanks. Some unvented breakers built on the bomb-proof theory have been put in service. These breakers have tanks of very heavy steel plate and plate covers welded or riveted together, and no attempt is made to vent. Trouble has been experienced, at times of unusually severe interruptions, in maintaining the bushings intact. It is quite possible to design the tank to withstand a tremendous internal pressure, but the porcelain bushings are not generally so designed and are, consequently, shot out of

their supporting flanges much after the fashion of a bullet out of a gun. It, therefore, seems far better to recognize the possibilities of excessive pressures and make provision for venting them out of the breaker than to attempt to build the tanks to withstand great pressures, with the attendant hazard of a possible failure of some part and consequent damage to adjacent equipment.

POSSIBILITY OF MAINTENANCE IN SERVICE

Maintenance of Insulation.

In operation, an oil circuit breaker must retain the ability to interrupt short circuits which it had when new and when it was initially installed. This is a maintenance problem and falls upon the operating companies using the breakers. The design of the breaker, however, must be such as will permit of convenient maintenance, or the work will not be done and the breaker will not continue to function as it should.

The insulation of the breaker must be designed with liberal factors of safety for the voltages to be encountered in service. When, in the ordinary course of usage, the insulation value falls below a safe operating limit, it must be possible to restore it. Insulators and bushings have been reasonably well standardized, and maintenance usually consists in wiping off accumulations of dirt and adding oil in the case of oil-filled bushings.

Inside the tank, the oil is subject to two influences tending to reduce its insulating value: First, the oil may become polluted, due to carbonization and break down due to the action of the arc, and, second, the breathing of the breaker may draw moisture into the tank.

As has been pointed out in previous discussion, anything tending to reduce the kilowatt-seconds of energy delivered to the oil will increase the rupturing capacity of the breaker, and clean oil of a high insulating value is essential to the best results, both from the standpoint of the breaker itself

and from that of the operation of the system of which it is a part.

Oil should never be permitted to fall below an insulating value of 15,000 volts for a $\frac{1}{10}$-in. gap, as measured on the standard testing equipment for the clearances in general use in modern oil circuit breakers. Moisture in the oil quickly reduces its insulating qualities, but, so far as is known, no successful provisions have been made to control breathing in a high-tension oil circuit breaker and dry the air before drawing it inside the tank.

Maintenance of Operating Parts.

It is evident that satisfactory circuit-breaker operation is contingent upon maintenance of all of the mechanical working parts of the breaker, in order to keep them in proper condition for operation when called upon to function. Many power companies maintain a continuous record of the performance of their oil circuit breakers through the use of a form sheet similar to that shown in Figs. 25 and 26. These form sheets are filled out each time the breaker is called upon to interrupt a fault current or a major overload which approaches the interrupting capacity of the breaker. In this way, the actual service operation of different breakers is compared and valuable data are at hand for reference when deciding upon additional or replacement breakers for the same or a similar station.

It is, also, becoming quite general to install operation counters on the closing mechanism in order to keep a record of the number of times that the breaker is operated. Values are assigned to operations under no load, normal load, and fault conditions, which places a weighted equivalent on each class of breaker operation. A standard number of operations is assigned to the breaker, and it is required that it be completely inspected each time that this number is reached. All necessary maintenance work is done at the time of this inspection, and the breaker is put back into service again for another series of operations. Such a system of breaker

PACIFIC GAS AND ELECTRIC CO.

RECORD OF OIL CIRCUIT BREAKER MAINTENANCE

(Instructions on Reverse Side)

Station ________ Month ________

BREAKER NO.	TYPE	LINE KV.	DATE LAST OVER-HAULED	OPERATIONS CONTINUED FROM LAST MONTH	TOTAL NUMBER OF UNIT OPERATIONS AS OF DATES BELOW																															DATE OVER-HAULED	DATE OF LAST OIL TEST
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31		

FIG. 25.—(Front.) Typical maintenance record.

PACIFIC GAS AND ELECTRIC COMPANY

RECORD OF OIL CIRCUIT BREAKER MAINTENANCE

This form shall be properly filled out and kept on file in each station for all oil circuit breakers operating at 6600 volts or over, excepting breakers on motor generators which are not operated when machines are in parallel or under load; such breakers shall be overhauled every six months. In filling out this record form, breakers should be grouped in accordance with their operating voltage.

A unit operation is defined, for the purpose of this record, as the opening of the circuit breaker under normal load with no trouble on the circuit.

When a circuit breaker is opened under service conditions, the foreman or operator will value such duty in terms of unit operations. The number of unit operations thus assigned shall be decided by the foreman or operator in accordance with his judgment of the duty imposed on the breaker in opening the circuit, based on past experience with the particular breaker involved.

The number of unit operations assigned to each opening of the circuit breaker shall be entered in the Log Book with the entry regarding such opening. At the end of the day the total number of unit operations assigned to each circuit breaker for that day shall be added to the previous record and the resultant sum entered in the proper column of this form.

Circuit breakers shall be inspected and overhauled after 125 unit operations. If immediate overhauling is not possible after 125 unit operations, the record of operations must be continued to show the total number of unit operations prior to overhaul.

In case the total of 125 unit operations is assigned to a breaker before the end of the month, the date of overhauling shall be entered in the proper column on the line for that breaker and a new line started for that breaker.

Overhauling implies thoroughly inspecting the breaker, including the control mechanism, dressing or renewing contacts, reconditioning oil and making such other repairs, replacements and adjustments as may be found necessary to replace the circuit breaker in first class operating condition.

The oil in circuit breakers operating on voltages from 6 KV to 30 KV inclusive shall be tested every six months, above 30 KV every three months, irrespective of whether or not the circuit breaker has been operated. Whenever the oil is found to test below 17,000 volts with .1" gap, it should be filtered and brought up to 22,500 volts or more with .1" gap.

In all cases where a breaker has not been tripped either manually or automatically during a period of six months (or less when local conditions require), it shall be inspected as thoroughly as possible from the outside and the control mechanism shall be tested to insure its opening automatically when called upon.

Fig. 25.—(Back.) Typical maintenance record.

maintenance requires some discretion on the part of the operator responsible for the maintenance of the operating record, since his judgment on the severity of interrupting

OIL SWITCH OPERATING RECORD

Operating Company ....

Switch Location .... Date .... Time .... A.M. P.M.

Company No. or Designation .... Circuit Voltage ....

Manufacturer's Name .... No. ....

Rated Voltage .... Oil Used ....

Rated Current Capacity:—Carrying .... Rupturing ....

Type of Switch:—Automatic .... Non Automatic .... No. of Breaks ....

Nature of Overload:—Ground .... Single Phase .... Three Phase ....

Approximate Current Interrupted ....

No. of Automatic Openings since Last Overhaul ....

Findings:		Phase A	Phase B	Phase
External	Bushings			
	Tops			
	Tanks			
	Oil Spillage or Leakage			
Internal	Bushings			
	Blades			
	Contacts			
	Oil: dirty, wet or carbonized			

Was Opening Satisfactory ....

General Remarks ....

FIG. 26.—Typical operating record.

duties which the breaker has performed determines the equivalent value which he places upon the number of operations and, consequently, the frequency with which the breaker is inspected.

CHAPTER VII

FACTORS DEPENDING UPON CIRCUIT CONDITIONS

CIRCUIT CHARACTERISTICS

THE oil circuit breaker has practically no control over the nature or amount of kilovolt-amperes which it will be called upon to interrupt in service. These factors are governed by the characteristics of the circuits connected to the breaker and determine the interrupting capacity which should be available in the breaker successfully to clear a circuit and isolate trouble.

Up to the time that manufacturing companies discontinued the practice of making guarantees as to the rupturing capacity of their breakers, it was usually considered that the most severe condition to be imposed upon a circuit breaker was a balanced polyphase short circuit at the generator terminals of an ungrounded system. This opinion has been voiced many times, especially in the publications of the manufacturing companies and in papers and discussions before the A. I. E. E. (35).

That this assumption was erroneous has been intimated in several recent papers and discussions on transmission-system stability presented before the A. I. E. E. but, so far as can be determined, has nowhere been definitely stated as a fact. In the part devoted to tests and data, this point will be considered in detail and evidence offered to prove that the balanced polyphase short circuit at the generator terminals is a much less severe condition for switch operation than others encountered in service.

The papers and discussions on system stability, without exception, set forth the desirability of *fast and accurate*

switching, and while an immense amount of data has been accumulated on methods of high-speed control of excitation on synchronous equipment, very little, if any, worthwhile discussion has centered on the oil circuit breaker, which is admitted, by all concerned, to be at least one of if not the most important disturbing elements entering into the problem of system stability.

The so-called "steady-state" stability conditions are set forth in laws fairly well known and in a usable engineering form. The problems encountered in connection therewith are largely economic The "transient-state" stability conditions, however, are not so simple and involve approximations and assumptions which render them difficult, if not impossible, of solution. The high-tension oil circuit breaker, due to its erratic behavior, as a circuit-interrupting device, is a large contributing factor in the problems of transient stability. Given a high-tension oil circuit breaker with a speed and positiveness equal to the present-day high-speed direct-current circuit breakers, and the transient stability problem is greatly simplified. It will then be susceptible of almost the same considerations as an economic study.

In any high-tension network, the current available on short circuit at a given instant and a given point depends upon the transient characteristics of the connected equipment. These transient characteristics are not well known at present for even the simplest of equipment and, for complicated combinations in an extensive network, not at all known. The circuit characteristics of which knowledge is required are a complex quantity involving both magnitude and phase relationship of all of the characteristics of generating, load, and connecting equipment.

For a balanced polyphase short circuit, where certain definite characteristics are known (although too often assumed), it is possible to calculate the short-circuit current for a given condition, provided the network is relatively simple. Present-day networks, however, are almost all operated with the high-tension circuits grounded, and as

high as 95 per cent of the total number of troubles appear as phase-to-ground short circuits. The balanced polyphase short circuit is a rare occurrence.

Single-phase short circuits to neutral or ground on a Y-connected high-tension network introduce complications so great that even the simpler networks have transient characteristics too complicated for calculation with present-day knowledge.

In each piece of rotating equipment and with transformer banks connected Y-delta, there is a phase-balancing or phase-converting action tending to equalize the phase voltages. This balancing action is applied through the transient impedance of all the equipment between the rotating equipment and the short circuit. The amount of such balancing action, as well as the short-circuit current available, is dependent upon the stored energy WR^2 of the rotating mass, and its rate of delivery depends upon the transient characteristics of the network, *i.e.*, on the drop in voltage and change in phase at the terminals of each piece of rotating equipment. From the foregoing it is evident that a short circuit from conductor to ground can and does have entirely different characteristics for different parts of a high-tension network. Practically all successful high-tension networks in operation today employ the grounded Y-connected system. The few that remain completely insulated require more insulation for the same transmission voltage and are beset with a number of troubles quite apart from the scope of the present discussion. Since, in practice, some 95 per cent of the high-tension trouble has been found to occur as short circuits from conductor to ground on Y-connected systems, it is important that circuit-breaker action be designed primarily to meet that condition (36).

As has been previously stated, the problem of system stability is dependent upon fast and accurate switching. This, in turn, means that it is essential to have the maximum reliability in high-tension oil circuit breakers, and additional data are needed for the solution of the complete

problem, which includes, besides that of the circuit breakers themselves, the problem of proper relaying and switching out of phase-to-ground faults (37).

A paper presented before a convention of the A. I. E. E. has the following to say on the subject:

> It has been brought out that one of the main factors in reducing disturbance and preventing loss of synchronism between the generating and receiving ends of a transmission system is the rapidity with which relays and switches can be made to isolate any trouble. It appears very probable that, by a material reduction in the time now taken, troubles could be successfully cleared when transmitting much greater amounts of power than at present and this same high standard of service could be maintained. Looking at this from another viewpoint, systems that might be furnishing but mediocre service would have that service vastly improved in quality by such change in switch operation, provided the transmitted load were not changed. On the other hand, unless it is possible to get extremely fast switch operation, less shock is produced when one end of a faulty section is cleared a short time after the other.

THE CHARACTER OF THE SHORT CIRCUIT

The amount of current flowing into a short circuit depends upon the impedance of the circuit and the voltage impressed. In practice, practically all short circuits on high-tension equipment are in the form of arcs for the greater portion of their continuance, and the problem becomes one of determining the resultant of two arcs in series, one in the oil circuit breaker and the other at the point of trouble. Until a great deal more is known concerning the many factors involved, no solution of such a problem is possible.

Some empirical data have been set down for very limited conditions of arc action, but even the limited conditions have not been completely described. So far as can be determined, there is at present no method of predetermining the action of a probable condition in a series arc circuit from given data on a known circuit. Apparently, no conclusive and worthwhile data are available on the effect of the char-

acter of the short circuit itself as affecting the operation of an oil circuit breaker.

PHASE RELATIONS AT INSTANT OF SHORT CIRCUIT AND TIME TO COMPLETE THE INTERRUPTION

The initial current surge for equipment connected close to a fault, *i.e.*, through low resistance and reactance, is largely determined by the point on the voltage wave at which the short circuit occurs. The classical textbook diagram of the rate of current decay of a short-circuited alternating-current generator, which is frequently included in the literature on oil circuit breakers, is correct only for one specific case—a short circuit at the generator terminals. Such a short circuit is extremely rare in operating practice, and when one does occur the trouble is invariably cleared by the low-tension oil circuit breakers. For such a condition, the high-voltage oil circuit breaker is called upon to handle the current fed into the short by the connected transmission system which, as was previously explained, may decrease, remain constant, or even increase for a period of a half second or longer.

From the standpoint of system stability, the point on the voltage wave at which a short circuit occurs is important. With present-day high-voltage breakers, however, the time elapsing before the contacts part a sufficient distance to interrupt the circuit is so great that an approximate steady-state condition is reached and conditions which existed at the instant of short circuit no longer apply. When circuit breakers are built which will interrupt the high-tension circuit in a half cycle, the particular half cycle which will give the best result can be selected. This is not a Utopian vision but an attainable goal which can and will be achieved. Speed of oil circuit breaker operation is essential, and development must go along the lines of increasing speed. Many problems now present will be automatically solved when the half-cycle breaker is finally perfected.

NATURE OF INTERRUPTION

Present-day oil circuit breakers do not interrupt the several phases of a polyphase circuit simultaneously. It is a practical impossibility to adjust and maintain equipment of this type to such a degree of mechanical precision, and even if it were possible to part all contacts at the same instant, an arc several inches long under oil is too unstable and subject to too many variable influences to permit several of them to be simultaneously extinguished. As a result of this progressive interrupting of the several phases, there is a phase-balancing action between the circuit being opened and the rest of the system which causes the contacts of the several phases successively to interrupt larger and larger values of current (38).

In every interruption of a high-tension circuit under either normal or short-circuit conditions, this action is evident, to some extent, if the circuit is part of a network. It is particularly noticeable when interrupting circuits having a considerable charging current such as long high-voltage transmission lines. As has been repeatedly stated, a balanced polyphase short circuit rarely occurs in practice on a high-voltage transmission line. When one does occur, it seldom remains a balanced polyphase short circuit up to the time of interruption. It would, therefore, seem that the breaker design should be based on other factors than the ones which have generally been accepted as the basis of design, and which have actually been proved in service to be less severe than other conditions which may obtain in service.

RESONANCE

There is another factor to be considered in connection with the nature of the interruption of a high-voltage circuit, and it is probably the most important and least understood of all the phenomena occurring in an oil circuit breaker when interrupting a circuit. At the instant the contacts part,

an arc is established. The arc has a so-called "negative-resistance" characteristic, due to the fact that the initial stream of ions and electrons under the influence of the high-potential gradient causes additional ions and electrons by collision. In effect, this increases the cross-sectional area of the arc and thereby reduces the resistance of the circuit. The action is accumulative, more current producing additional ionization and increased ionization reducing the resistance and permitting more current flow, the limit tending to approach zero resistance for infinite current.

At the start of the break in an oil circuit breaker, there is relatively very low potential across the arc, and the effect of the arc in the circuit as recorded on an oscillograph film is scarcely noticeable. As the contacts part further and the voltages across the arc increase, the current growth in the arc for each cycle is determined more and more by the characteristics of the connected circuits.

The ability of an arc to convert from one frequency to another is well known in connection with radio communication but is little appreciated by transmission engineers, and practically no data for the calculation of the effects of two arcs in series in a circuit containing capacity and reactance are available. The subject has been treated by Dr. C. P. Steinmetz (39), and he has set down numerous mathematical formulæ for the treatment of the problem, but its practical solution is extremely difficult, due to the complex nature of the quantities involved in a transmission network and to the necessity for making a great many assumptions when setting down the premises in any given case. In his paper, Dr. Steinmetz took up the consideration of an arc shunted by an inductive circuit containing capacity and supplied with voltage over an inductive circuit from an alternating-current source. It is shown that in such a system currents and voltages of two distinct frequencies may continually exist, of which one is the machine frequency and the other a high oscillation frequency. It is further shown that the voltage of the latter is limited only by the resistance of the

oscillating circuit and in low-resistance circuits may build up to very high values. The high oscillation frequency is essentially limited to the circuit shunting the arc and but little of it enters the supply circuit, while the supply frequency enters the shunt circuit to a limited extent only. Both frequencies are superimposed in the arc, which is acting as the frequency converter.

From the foregoing, it is evident that other frequencies and voltages than those originating in the generating stations must be considered in the design and operation of an oil circuit breaker, and it may readily happen that these secondary voltages can impose duties on the breaker beyond the range of voltages and currents for which it was designed. In the light of the complex nature of the problem, it is not possible of exact mathematical solution, and here is one of the reasons for the necessity of actual *field* tests to substantiate the interrupting capacity of a given high-voltage oil circuit breaker.

As has been stated several times previously in this text, and as will be proved in the part devoted to tests, it is from fifteen to twenty times as difficult, ampere for ampere, to interrupt the charging current on a long high-voltage transmission line as it is to interrupt a short circuit in which the current is approximately at zero power factor lagging. It also appears to be more difficult to interrupt a line-charging current than it is to interrupt a similar current at zero leading power factor supplied by rotating equipment, although no tests are available definitely to fix the ratio. The interruption of line-charging current is apparently one of the most difficult duties which can be imposed on an oil circuit breaker, and yet in the routine and emergency switching of long high-voltage transmission lines it is an ever-present factor.

In practice, it is not possible to interrupt simultaneously all phases of a transmission line at both ends when clearing trouble. As a result, for each line cleared by its oil circuit breakers, one or more phases in the breaker will be required

to break the charging current through the arc. Manifestly, a great many combinations may be set up where an oil circuit breaker is installed at each end of a line and with their contacts all breaking the circuit at different instants. The result, however, is that one or more contacts will inevitably be called upon to interrupt charging current and thereby be called upon for severe switch duty.

From an operating standpoint, all arguments are in favor of an oil circuit breaker which will interrupt the circuit at the end of the first half cycle of arc after the control relays have closed their contacts. Any greater time is detrimental to service and equipment and is, at present, tolerated only because no alternative is possible.

The duty imposed upon oil circuit breakers by the requirements of high-speed operation is admittedly severe, but it is essential to the satisfactory operation of large transmission networks, and oil circuit breakers must be designed and built to meet the rèquirements of the users.

On this phase of the subject, the vice president in charge of construction and operation of one of the Pacific Coast utility companies says (40):

> The function of the operating company is to give service—not service when conditions on the system are absolutely right, but service under all conditions. If the manufacturers are unable, with their present equipment, to provide facilities to the operating companies with which they can give service, the operating people, I think, feel it is up to the manufacturers to provide those facilities, if it is humanly possible to do so, to give that service.
>
> We realize that the operating companies and the manufacturers are up against two problems: first, to provide a switch that will function properly from an electrical standpoint; and the other problem is to provide that switch at a price that the operating companies can afford to pay. Only very recently, within the last two years, the company with which I am associated had occasion to purchase a good many 220,000-volt oil switches. I am not at liberty to quote prices, but the prices of those switches were not low: They were a very important item of expense.
>
> So, the manufacturers must get this idea firmly fixed in their minds: *That systems cannot be designed around the oil switches.*

You can't arrange your circuits so as to meet the convenience of the designers or the manufacturers. The public demands service. You must take on any load that comes along, and supply that scrivce. If the present design of switches is inadequate to handle the loads that are carried, then they must be changed, because, after all, when you consider that there is a legal and a moral responsibility resting upon the operating companies to give service, it is up to the manufacturers and to the operating companies to provide facilities for giving that service.

Again, in 1928, from the same executive (41):

As an interconnected network grows, and the amount of power delivered into it increases, the necessity for having dependable switches becomes of increasing importance. The construction of high-voltage switches has been materially improved during recent years, but there has been practically no change in the general design. Failure to keep pace with the development of other facilities used in connection with the production and transmission of high voltages has made them the weakest link in a power system.

The first attempt to build switches for operation at voltages as high as 60,000 was made in 1899 by the engineers of the Bay Counties Power Company, now a part of the Pacific Gas and Electric Company's system. The consolidation and interconnection of a number of smaller systems soon made it apparent that switching could no longer be done on the low-voltage side of the transformers. The manufacturers had not yet developed switches for this voltage. To meet a situation precedent to satisfactory service from an interconnected network, it was necessary for the company to design and build its own high-voltage switches. The first attempts were necessarily crude.

Improvements in the design and manufacture of bushings have eliminated material used in the original design, and present-day switches are much more rugged and dependable than those of 25 years ago. Although these improvements have added to the mechanical and electrical efficiency of the equipment, they have also increased first cost to a point which, with the usual number of air switches for by-passing and cutting out the high-voltage oil-switch equipment, in a modern generating plant, represents an investment equal to 50 per cent of that in transformers.

No other piece of electrical equipment offers greater opportunity for improvement than high-voltage switches. The very satisfactory operation of the two 220,000-volt lines in California has proved beyond question the practicability of going to even

higher voltages just so soon as the economics of the situation warrant. What the future may bring forth in the way of improvement in high-voltage switches remains to be seen.

Along the same line, the vice president in charge of operation of a Southeastern utility says (42):

> If I had any criticism to make of the manufacturers, it would be that they have in the past years spent too much time trying to convince the operators that what they had manufactured was exactly right and there was nothing whatever wrong with it—instead of correcting obvious faults that have been brought out in operating practice. . . . When you have come down to adjusting breakers to two-thousandths or four-thousandths of an inch, to get them to operate properly, and if when you fail to do that you break the operating rods or links, or something else, it is too delicate a piece of mechanism to give to the ordinary electrician. . . . Then we want the switches to come onto our system so that we can work with them, so that ordinary men and not factory men can put them up, can repair them and give service to the people to whom we are supposed to give service with them.

The oil circuit breaker is still a big problem to the operating companies and bids fair to continue to be a big problem unless some radical new development is brought forth. On the one hand, there are the operating companies, growing year by year in the amount of installed capacity and, consequently, demanding increased rupturing capacities from their oil circuit breakers, and, on the other hand, the manufacturing companies attempting to meet these demands with varying degrees of success and with various methods of switch design. There is a great lack of agreement as to method, and the purchaser of an oil circuit breaker is put to the necessity of weighing the evidence submitted by each manufacturer and then choosing his breaker. None of the evidence is conclusive. There is no way in which a high-rupturing-capacity, high-voltage oil circuit breaker can be tested except in actual service, and the purchaser hesitates to invest $20,000 to $30,000 or more in a piece of equipment without definite assurance that it will perform the duties expected of it.

The authors of this text have been connected with the electric-power industry for the past 15 years and, in the course of everyday events, have had contact with the installation and operation of many oil circuit breakers. That there was a great lack of information in the hands of the utility companies concerning breakers, and evidently room for improvement in design and operating characteristics, has been evident for a long time. The entire situation has been so aptly summed up in a letter writtern by M. M. Samuels of the J. G. White Engineering Corporation of New York City and published in the *Electrical World* of Feb. 5, 1927, that it is here produced in its entirety as representing the general state of affairs in oil circuit breaker design and, in a measure, setting forth the reason for this text. Mr. Samuel's letter follows:

To the Editor of the Electrical World:

> Your editorial in the issue of Jan. 22 entitled "Hindrances to Circuit-breaker Development" is certainly timely, and it may be hoped that your remarks will initiate a discussion of the question which will gradually break the mysterious cloud surrounding it. I am sure, therefore, that you will permit me to express my opinion freely, even though it may, in some respects, be diametrically opposite to your own.
>
> First of all, your editorial is based altogether on the manufacturer's viewpoint, if, in the existing confusion, it is at all proper to speak of a viewpoint. The manufacturers are spending enormous amounts of money on research and development, to be sure, but who finally pays the bill? Obviously, the public utility that buys the breaker. Why should breakers be so expensive if it were not for the fact that development charges have to be paid? Because a breaker, aside from the development charge, is nothing more than so many pounds of manufactured metal and insulating material which cost so much a pound.
>
> What has been accomplished through all these years of research and millions upon millions of expenditures? Some one once found that oil is a good medium for switching—a new and revolutionary idea then and very useful ever since. Then some one very ingeniously invented the principle of the new explosion chamber, no

doubt a radically new idea and very useful, in some cases. Then some one had the idea of the multibreak, an imitation of the multibreak fuse, but likewise a very useful appliance.

What else? Nothing. Make the tanks larger and of heavier steel, use more oil, make heavier contacts and heavier springs, and don't forget the old bell crank. It would appear that switch-mechanism designers never heard of any other kinematic device except the bell crank.

Rupturing-capacity guarantees were always a joke. No manfacturer was ever ready to submit the figures upon which his breaker rating was based. When a transformer or a motor or a turbine is purchased, there is no mystery about guarantees; the constants and calculations upon which they are based are available. Not so in the field of breakers. The manufacturer is always at an advantage, for two principal reasons: When a motor heats above the guarantee, the fact can be ascertained by a child; but when a breaker blows up, no power on earth can determine what really caused the accident. It may have been bad oil; it may have been poor adjustment; it may have been anything. The second advantage that the manufacturer has is that a certain time interval—0.2 sec., 0.3 sec., etc.—is assumed from the beginning of the short to the time of the opening, based mostly on shop or laboratory tests, and this time interval is probably always longer in actual shorts on a property, because old Mr. Bell Crank and the rest of the family are no doubt somewhat rheumatic after a switch has been in operation a certain time.

Large public utilities did make a great many tests recently at their own expense—the only tests of any value so far. But why did these public utilities undertake these tests? Why did they select breakers instead of any of the other thousands of articles which they are regularly purchasing? They found that they were spending millions on switches about which they could get very little information, and after spending all these millions they found themselves losing fortunes through service interruptions without any possibility of every collecting anything from the manufacturer on a rupturing-capacity guarantee. Therefore, they made up their minds that they are going to find out for themselves. All credit to them. If they keep up the good work, they will find out a great deal. They have already found enough to make the manufacturers refuse to give them guarantees on rupturing capacity. Who ever paid money for a piece of property because the man who sold it "believed" that he had a deed?

What is needed in the switching game is not merely bigger tanks,

more oil, heavier contacts, etc., but new ideas, radically new ideas. Not development, but invention.

What is the matter with the American inventive genius? In what other fields are men working in expensive laboratories, day in and day out, having unlimited research means at their disposal, and producing nothing? The manufacturers have at their disposal a great many men of genius—scientists, who continually startle the world by their discoveries and their inventions. Why don't they let them loose on switch investigation? The buying public has lost confidence in switches, it is up to the manufacturer to bring out new ideas, new theories and new principles, new mediums, besides oil, and thus regain their confidence. This is the basis of all sound business.

M. M. SAMUELS
J. G. White Engineering Corporation
New York City

There can be no doubt that the letter will provoke discussion and differences of opinion. The fact nevertheless remains that of all electrical apparatus now offered by the manufacturing companies, the oil circuit breaker is the only one not subject to actual tests and guarantees. Conflicting claims are made none of which can be definitely proved or disproved except by actual operation of the switch in service. If it fails, there is no recourse, and, in self-defense, the public-utility companies have been obliged to carry on extensive tests and investigations to satisfy themselves as to the relative merits of the several types of breakers offered.

The manufacturers have felt the pressure which the operating companies have brought to bear for improvement in oil circuit breakers, and since the work of writing this text was started, one very important new principle has been announced by one manufacturer. It is the so-called "Deion breaker," brought forth by the Westinghouse Company (43).[1] Thus far, the breaker has been designed only for the lower-voltage, high-current duties, but as it is still in the experimental stage, further study may point the way to its application at the higher voltages. From the data published, it

[1] See also deion grid pp., 120–125.

would appear that this type of breaker is somewhat in the class of the magnetic-blowout breakers, its greatest effectiveness being realized with heavy currents. Just how it will behave with the relatively low currents at high voltage remains to be seen.

The deion breaker offers several important advantages. In the first place, there is a complete absence of oil, which is an ever present menace, due to its inflammable nature. Secondly, the deion breaker is remarkably fast in circuit interruption, rarely requiring more than a cycle to complete the interruption. The ultimate goal of a half-cycle breaker seems to be coming up over the horizon.

The General Electric Company is conducting extensive experiments with the vacuum type of breaker but, thus far, has made no public announcement of the results of its investigations. In this case, the problem is a mechanical one—that of maintaining a sufficiently high vacuum in the contact chamber. Here, again, there is promise of a fast circuit-interrupting device if the problems of design can be overcome. The oil is again eliminated from the picture and the breaker interrupts remarkably high currents at high voltage with scarcely perceptible arcing.

Two predictions made by the authors more than two years ago were that we should one day have a circuit-interrupting device capable of clearing a line in a half cycle and that the oil circuit breaker as we now know it would probably be superseded by some radically different piece of apparatus. Both predictions seem in a fair way to be fulfilled in the not very distant future. In general, it may be said that the output of electrical energy is increasing at such a rate that it about doubles in 10 years. Some idea may thus be formed of the rapidity with which transmission networks are growing and the concentrations of power increasing. Oil circuit breakers purchased only a few years ago are approaching the limits of their rupturing ability, and some uneasiness is felt regarding the same general type

of equipment simply magnified in size to meet the greater duties. The new types hold a promise long looked forward to, and it is very much to be hoped that methods will be found to overcome the present obstacles to regular production and use.

PART III

MODERN HIGH-VOLTAGE BREAKERS

CHAPTER VIII

GENERAL INFORMATION

THE selection of an oil circuit breaker for a given installation in a high-tension transmission system requires, in addition to a knowledge of the characteristics of the circuit in which the breaker is to operate, a full knowledge of the breaker under consideration for the application. It is difficult to compare breakers of different manufacture. The theories of design vary greatly, and actual full-capacity tests cannot be made, owing to the extreme size of the testing equipment necessary to prove the interrupting capacities of the larger, high-voltage breakers. Decisions as to the proper breaker for the installation must be based upon a knowledge of past performance of similar breakers or a study of the constructional details of proposed breakers and an assumption regarding their probable action under *circuit* conditions.

An effort has been made by the National Electrical Manufacturers Association (N. E. M. A.) and the A. I. E. E. to standardize oil circuit breakers in so far as the ratings and test requirements are concerned. This has resulted in limiting the number of standard voltage and current ratings and reduces the number of breakers to be considered for a given transmission voltage. Comparisons of interrupting capacities are not readily made. In many cases, the published interrupting capacities are calculated values, based upon extrapolated curves and assumptions made from tests on lower-voltage breakers. No positive guarantee of interrupting capacity is given, but all manufacturers insert the following clause in their specifications and contracts:

Because system maintenance and operating conditions are beyond the control of the manufacturer, interrupting ratings of the oil circuit breakers cannot be guaranteed, but this does not relieve the manufacturer of his contract obligation to deliver oil circuit breakers having interrupting ratings as specified.

The foregoing clause is used for the protection of the manufacturers against third-party liability. In this matter, oil circuit breakers differ greatly from other electrical equipment such as generators, motors, transformers, etc., in which the performance can be accurately predicted from theoretical calculation, and actual tests conducted to prove operation. Large-capacity, high-voltage breakers must be bought and installed without actual full-capacity tests.

If it were possible actually to test oil circuit breakers at rated interrupting capacity, the results would not be so conclusive and comparable as is the case with other electrical equipment. They do not lend themselves to such rigid specification of performance details. The matters of amount of contact burning, oil throwing, oil pollution, etc., are comparable to a degree, and all must be considered in deciding the merits of a given breaker but cannot be set down in definite figures for comparison as to efficiency of operation.

The A. I. E. E. standard for the interrupting performance of oil circuit breakers specifies that

1. An oil circuit breaker shall perform at or within its interrupting rating without emitting flame.
2. At the end of any performance at or within its interrupting rating, the circuit breaker shall be in the following condition:
    a. *Mechanical.*—The breaker shall be substantially in the same mechanical condition as at the beginning.
    b. *Electrical.*—The breaker shall be capable of carrying rated voltage, and its main current-carrying parts shall be substantially in the same condition as at the beginning.

    After performance at or near its interrupting rating the interrupting ability of the breaker may be materially reduced, and it is not to be inferred that it may be reclosed after such performance without inspecting and, if necessary, making repairs.

A study of the above specification will disclose the opportunity for difference of opinion as to the fulfillment of requirements. "The breaker shall be *substantially* in the same condition" is not a *definite* requirement, and that which might be acceptable performance to some engineers would be rejected by others. Thus, it is seen that comparisons of interrupting capacities are difficult to make, and details of the breaker design and operating features must be considered together with the stated interrupting capacity of a given breaker when comparing it with another manufacturer's product.

RATINGS

The A. I. E. E. standardization rules require that the rating of an oil circuit breaker shall include the following items:

a. Rated current.
b. Rated voltage.
c. Rated frequency.
d. Rated current-interrupting capacity.
e. Rated short-time current-carrying capacity.

The N. E. M. A. has adopted the following as standard ratings for high-voltage oil circuit breakers:

Ampere Ratings.

The standard current carrying capacities at 60 cycles are 400, 600, 800 and 1,200 amp. Breakers shall carry rated current without exceeding an observable temperature rise of 30° C. Breakers for 25-cycle service shall be standard 60-cycle equipment, given its corresponding rating at 25 cycles. Standard oil circuit breakers are designed to meet A. I. E. E. tests at standard ratings at a minimum altitude of 3,300 ft. For apparatus intended for use at altitudes above 3,300 ft., the permissible temperature rise shall be reduced by 1 per cent for each 330 ft. by which the altitude exceeds 3,300 ft.

Voltage Ratings.

The standard voltage ratings corresponding to standard normal-system voltages are 73, 88, 110, 132, 154, 187, and 220 kv.[1] Oil circuit breakers are rated in r.m.s. volts based on a dielectric test of $2\frac{1}{4}$ times rated voltage, plus 2,000 volts for 1 min., at a specified altitude. As a supplementary test, breakers for outdoor use should withstand for 10 sec. a dielectric wet test at twice rated voltage plus 1,000 volts.

Application on Y-connected Systems.

In general, oil circuit breakers are applied on the basis of the full-line or delta voltage of the system. On systems having a full-line voltage of 220 kv. or over, however, breakers may be installed on the basis of the voltage to ground when the system is Y connected with one end of the single-phase transformer windings permanently connected to the core and case, which are suitably grounded, and with the oil circuit breakers so located and connected that, whether closed or open, they will not be energized by transformers the neutrals of which are not solidly grounded. When applying oil circuit breakers on the basis of voltage to ground, the circuit-breaker frame must be grounded and the dielectric test shall be 3.1 times the voltage to ground plus 2,000; the dielectric wet test shall be 2.73 times the voltage to ground plus 1,000; and the breaker shall have bushing spacing and length of stroke employed as standard for full-line voltage service conditions. This is an important consideration and permits a considerable saving in oil circuit breaker costs to systems operating Y connected with solidly grounded neutrals. In general, it means that hybrid breakers with full stroke and reduced insulation may be used on such systems. The 220,000-volt transmission system of the Pacific Gas and Electric Company is completely

[1] Changes March 1, 1930, to 69, 92, 115, 138, 161, 196, 230, and 345 kv. in N. E. M. A. ratings.

equipped with 187,000-volt oil circuit breakers, and several years of operation have demonstrated that the breakers are adequate for use on these lines. A comparison of the dielectric test voltages for the different conditions is given in Table I.

TABLE I.—COMPARISON OF DIELECTRIC TEST VOLTAGES FOR FULL-DELTA VOLTAGE AND GROUNDED-Y SYSTEMS

System voltage	Voltage to ground Y connected	Full-delta dry test, $2\frac{1}{4}\times$ rated volts $+2,000$	Grounded-Y dry test, $3.1\times$ volts to ground $+2,000$	Full-delta wet test, $2\times$ rated volts $+1,000$	Grounded-Y wet test, $2.73\times$ volts to ground $+1,000$
187,000	108,000	422,800	....	375,000	
220,000	127,000	497,000	395,700	441,000	347,700

These standard oil circuit breaker voltage ratings are based on installation at altitudes of 3,300 ft. above sea level or less. For application at other altitudes than those for which the apparatus is designed, the standard voltage rating of the apparatus should be multiplied by the factors given in Table II to obtain the modified voltage rating.

TABLE II.—CORRECTION FACTORS FOR ALTITUDE

Altitude, feet	Correction factor for apparatus rated on basis of different altitudes				
	Sea level	3,000 ft.	3,300 ft.	4,000 ft.	5,000 ft.
0	1.00				
3,000	0.91	1.00			
3,300	0.90	0.99	1.00		
4,000	0.88	0.97	0.98	1.00	
5,000	0.85	0.94	0.95	0.97	1.00
10,000	0.73	0.80	0.81	0.83	0.87

Frequency Rating.

The standard rating of oil circuit breakers is understood at 60 cycles unless otherwise specified. At and above 600 amp., both 25- and 60-cycle ratings may be given.

Current-interrupting Rating.

The interrupting rating of an oil circuit breaker is a rating based upon the highest r.m.s. current at normal voltage that the breaker can interrupt under the operating duty specified. The value of the current is taken during the first half cycle of the arc between contacts during the opening stroke. The standard operating duty cycle is the so-called "OCO + OCO" duty cycle, which consists of two unit operating cycles with a 2-min. interval between. The unit operating cycle starts with the breaker in the open position. It is then closed, followed immediately by its opening without purposely delayed action. The cycle is repeated at the end of 2 min. The condition required of the breaker after the completion of the above duty cycle under test has been set forth at the beginning of this chapter. Briefly, the breaker must operate without emitting flame and must be in *substantially* the same mechanical and electrical condition as at the beginning and able to carry rated voltage. Its interrupting ability may be *materially* reduced.

The conditions assumed in rating an oil circuit breaker include the stored electrostatic and magnetic energy of the system, the reestablishment of an arc under transient voltage conditions, and other variable conditions. These influences are considered as not differing widely in average systems and are to be taken into account in the *factor of safety employed in the rating* of breakers.

It is quite evident that there is room for differences of opinion as to oil circuit breaker performance. The nature of the apparatus is such that definite and rigid specifications cannot be laid down which will insure that test data are actually comparable. Also, the electrical characteristics of

different transmission systems vary greatly, and a breaker adequate to meet the requirements on one system may be severely taxed in meeting the same or lesser short-circuit requirements on another system, due to differences in resonance, phase balancing, system WR^2, power factor, etc. It is extremely difficult to simulate actual field conditions in factory tests. Oil circuit breakers are one of the most important items entering into the design and operation of high-voltage transmission networks, and yet there is probably less definite knowledge of how they will behave when operating under full name-plate rating than is the case with any other class of electrical equipment.

The standard steps of interrupting capacity rating as listed by the N. E. M. A. are given in Table III.

TABLE III.—STANDARD STEPS OF INTERRUPTING CAPACITY

Voltage	Arc, amperes	Approx. arc, kva.	Voltage	Arc, amperes	Approx. arc, kva.
73,000 (69,000)[1]	1,200	150,000	132,000 (138,000)[1]	3,300	750,000
	4,000	500,000		6,500	1,500,000
	8,000	1,000,000		11,000	2,500,000
	12,000	1,500,000	154,000 (161,000)[1]	2,800	750,000
88,000 (92,000)[1]	1,650	250,000		5,500	1,500,000
	6,500	1,000,000		9,400	2,500,000
	9,900	1,500,000	187,000 (196,000)[1]	3,100	1,000,000
110,000 (115,000)[1]	1,300	250,000		6,200	2,000,000
	2,600	500,000	220,000 (230,000)[1]	3,300	1,250,000
	5,500	1,000,000		6,600	2,500,000
	8,000	1,500,000	345,000	....	2,500,000

[1] These voltages to be standard for rating and for dielectric test basis with a maximum allowable service value of 5 per cent above these values. N. E. M. A. ruling effective March 1, 1930.

Short-time Ratings.

The short-time carrying capacity of an oil circuit breaker is the maximum r.m.s. current that should be passed through it for any period of time, however small. This limitation

may be imposed by either thermal or electromagnetic effect. The short-time carrying-capacity rating is given for a 5-sec. interval, and some manufacturers give, in addition, a rating for 1 sec. No standards of the value of the short-time carrying capacity have been adopted. In general, however, 5-sec. rating for oil circuit breakers of 73,000 volts and over is fifty times rated amperes but not exceeding 40,000 amp. The 1-sec. rating is usually placed at 40,000 amp. for high-voltage oil circuit breakers.

In preceding parts of this text, the oil circuit breakers have been classified in accordance with the method employed to achieve an accelerated break. This classification divides the breakers into three principal groups: (1) those employing quick-break secondary contacts, (2) those employing explosion-chamber contacts, and (3) those employing multiple-break contacts.

The same grouping will be followed in the consideration of the high-voltage oil circuit breakers now on the market, and the products of the several manufacturers will be presented in accordance with the type of break employed. The breakers built by the Westinghouse Electric and Manufacturing Company typify the quick-break secondary-contact type; those of the General Electric Company, the explosion-chamber type; and those built by the Pacific Electric Manufacturing Company, the Kelman Electric and Manufacturing Company, the Condit Electrical Manufacturing Company, and the Brown Boveri Company may all be classified as multiple-break oil circuit breakers.

CHAPTER IX

WESTINGHOUSE OIL CIRCUIT BREAKERS

The Westinghouse line of high-voltage oil circuit breakers is known as the "type G series" of breakers, the rupturing capacity being designated by numerals and letters following the type letter G. In each voltage class, the lowest current-interrupting rating begins with the numeral 1, as, for example, G–1, G–10, G–11S, etc., while the highest rating begins with the numeral 2, as, for example, G–22S, G–222S, or G–222AS. The G–1 breakers have elliptical tanks, while the G–2 breakers are of the round-tank type.

While there is considerable variation in the construction of the different forms of type G breakers, they have many features in common. Two methods of mounting are used in this line of breakers. Up to and including the 88,000-volt breakers, frame mounting is used. The pole units are assembled on a steel frame which supports them at a distance above the floor, thus allowing space for the tanks to be lowered and removed. This form of mounting is shown in Fig. 27. The higher voltage breakers are floor mounted, as shown in Figs. 28 and 29, thus allowing maximum insulation distances with a minimum overall height of the breaker. The tanks of the types G–1, G–10, and G–11 breakers are elliptical in form so as to allow the necessary distances from live parts to ground and still occupy the minimum space. The tanks of types G–22 and G–222 breakers are round. This construction provides the necessary mechanical strength required in these higher interrupting-capacity breakers. All tanks are made of boiler steel welded at the joints. The frame-mounted breakers have the tanks suspended from above and clamped against a gasket in a groove in the

base casting by means of bolts arranged around the periphery, thus forming a very secure seal. The tanks of the floor-

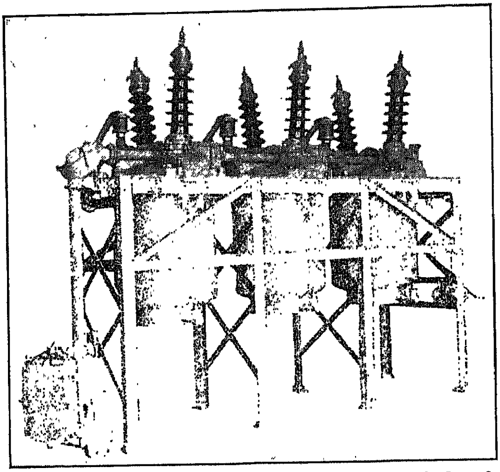


FIG. 27.—Frame-mounted Westinghouse G-222 oil circuit breaker for 50 kv.

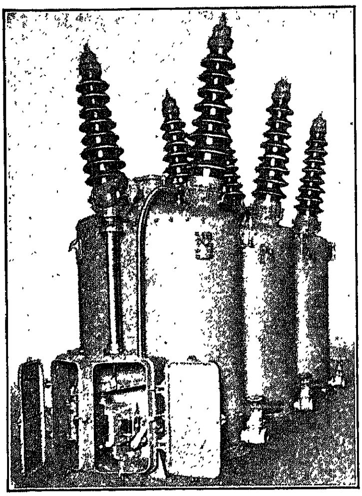


FIG. 28.—Type G-11, Westinghouse, 132-kv., outdoor oil circuit breaker.

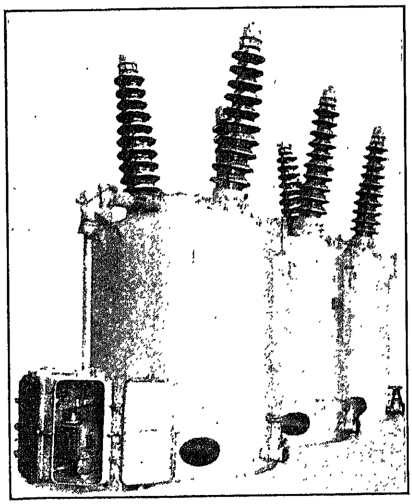


FIG. 29.—Type G-22, Westinghouse, 132-kv., outdoor oil circuit breaker.

mounted type rest on the floor and support the other parts of the pole units. A manhole is provided in the top of the tank through which a man may enter to make inspection

and adjustment of the inside parts. Where necessary, insulating-tank liners are provided which act as flash barriers and prevent the arc from reaching the tank.

A portable windlass type of tank lifter for raising and lowering the tanks of the frame-mounted breakers is used.

Practically the entire application of this line of breakers is for electrical operation. This may be obtained either by the use of the direct-current solenoid mechanism or the alternating-current motor mechanism.

Toggle mechanisms as used in the type G line of breakers are all of the same general construction and differ only in details. The moving contacts are attached through an insulated lift rod to the main lever. This lever is controlled by links in such a way that it gives a straight vertical motion to the lifting rod. The connection to the horizontal pull rod is made through a toggle link which straightens out in the closed position, thus giving a minimum force on the pull rod when the contacts are engaged. The horizontal pull rod operates inside a conduit, which connects to the bell-crank housing and, thus, to the operating mechanism through the bell crank.

A typical toggle mechanism is shown in Fig. 30. It is for use on the type G–11, 132,000-, 154,000-, and 187,000-volt breakers and, also, for the types G–22 and G–22A breakers of 110,000 volts and up. The main lever is attached to the lifting rod at one end and controlled by a guide at the other. It is operated by the closing lever, which is pinned near the center and pivoted at the other end. The closing lever is connected by a long toggle link to the toggle lever. This toggle link extends back along the side of the toggle lever over the operating shaft to the closing lever, whereas, in some types, the toggle link is extended out from the end of the toggle lever away from the operating shaft. The operating lever and toggle lever are keyed to the operating shaft but are in separate compartments. The pull rod connects the operating levers of the pole units together and is operated by a lever in the bell-crank housing. This, in turn,

is operated through a vertical rod by the operating mechanism. All moving parts are completely enclosed in weatherproof casings. An indicator is located on the bell-crank housing, as shown, to indicate the position of the breaker. Figure 30 also shows the balance springs located between the first pole unit and the bell-crank housing. The inner spring, shown in the figure, is omitted from the smaller breakers. The spring comes into action toward the end of the opening stroke when a collar on the operating rod strikes the spring

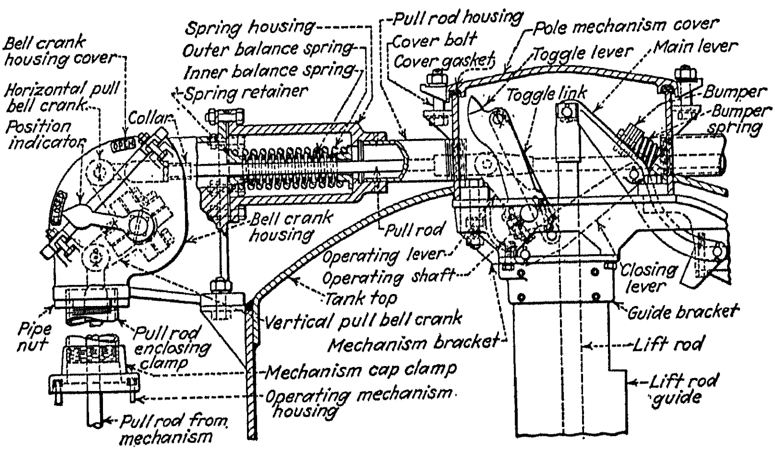


FIG. 30.—Westinghouse toggle mechanism.

retainer, causing the spring to be compressed, thus balancing the weight of the contacts.

All high-voltage Westinghouse oil circuit breakers are equipped with condenser-type terminal bushings. This type of bushing is made up of layers of insulating micarta wound around the terminal alternately with layers of tinfoil. The layers of tinfoil are stepped off at both ends to give the proper dielectric gradient. On the lower voltages the micarta is wound full at the ends, forming a protective layer. The insulation of the higher-voltage types is stepped off with the tinfoil. Protection for the steps is provided by means of porcelain arc shields (see Fig. 78). The upper end

of the bushing is protected, in the case of outdoor breakers, by a porcelain weather casing. The exposed upper end of the indoor bushings is protected by micarta tubing. A wire ground banding is provided at the middle of the bushing and a steel clamping flange over it, to serve as a support for the terminal bushing.

The contacts of all type G breakers are designed with the view of affording the maximum service with the least amount of maintenance. The current-carrying contacts are of either the butt or finger type, according to the amount of current to be handled and, in all cases, are protected by arcing contacts. In cases of the types G-1, G-10, and G-11

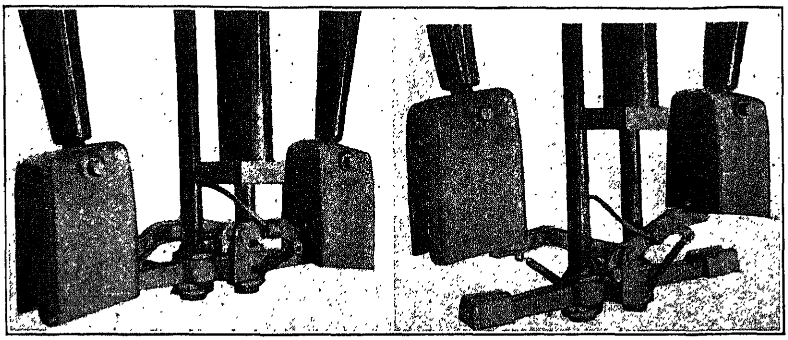


FIG. 31.—Westinghouse arcing contacts used up to 88 kv.

breakers below 132,000 volt, the arcing contacts are of the plain-break type, while on the other breakers they are of the high-speed type. There are two forms of high-speed arcing contacts, namely, the lever type, shown in Fig. 31 and used on the types G-22 and G-222 up to and including the 88,000-volt breakers; and the bayonet type, used on the higher-voltage breakers (see Figs. 32, 33, and 34).

The ordinary butt type of contact construction uses one large main-butt contact carrying the main circuit and an auxiliary arcing-tip butt contact. This contact is readily adjustable and is used on 400-amp. rating for 73,000- and 88,000-volt types G-1, G-10, and G-11 breakers and on the

600-amp., 110,000-volt, type G–10 breaker. Contact pressure is maintained by a heavy spring under each butt, and current is carried into the plunger by a shunt. The plunger usually is mounted on the stationary part of the contact.

The wedge type of finger contact is used on all types G–1, G–10, and G–11 breakers of 600 amp. and over, below 132,000 volts, except the G–10, 110,000-volt breakers. These finger contacts are extremely flexible in all planes.

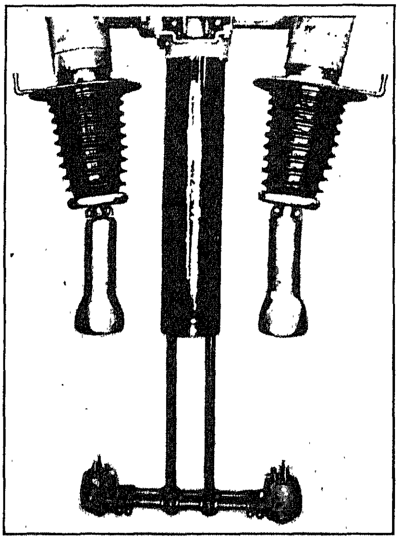


Fig. 32.—Westinghouse contact assembly above 88 kv.

The moving contacts use a wedge of cast copper accurately machined and provided with a butt-type arcing tip which is renewable.

Each of the stationary fingers is of drop-forged copper, machined on the contact surface and provided with a laminated-copper shunt backed up by a steel spring. Pressure is exerted on each finger by a pressure spring.

The lever type of high-speed contact (Fig. 31) is used on the types G–22, G–22A, G–222, and G–222A below 110,000 volts. The main contact consists of a set of heavy fingers mounted on the terminal foot and engaging with the blades

on the moving element. The arcing contact fingers are mounted on the terminal foot and engaging with the arc tips which are fastened on the ends of moving levers pivoted at the center of the moving element and actuated by springs, as shown. This type is known as the "roll-in" type, because of the rolling motion of the arcing fingers as the moving arcing tip passes between them. A shoulder on the

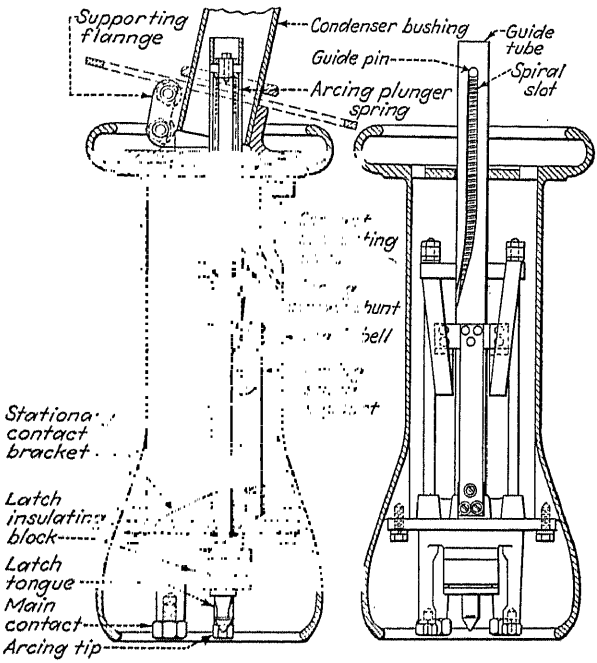


FIG. 33.—Details of stationary member of Fig. 32.

finger parts prevents the moving tip from releasing before the proper time.

The illustration in Fig. 31 does not clearly show the location of the arcing tips, but they are mounted on the outside of the main contacts. There is a recess in the wedges of the main contacts into which the lever of the high-speed contacts fits when the switch is in the closed position, thus permitting the mounting of the final break contacts on the outside of the

main contacts. This is the most advantageous position in which to have the final break and arc occur, since the magnetic effect on the arc tends to cause it to move outward and, hence, directs it away from the main current-carrying contacts and minimizes burning. This type of arcing contact will give a speed of break about three times the speed of the plain-break breaker having no arcing tips and is effective in increasing the rupturing capacity of the breaker, provided

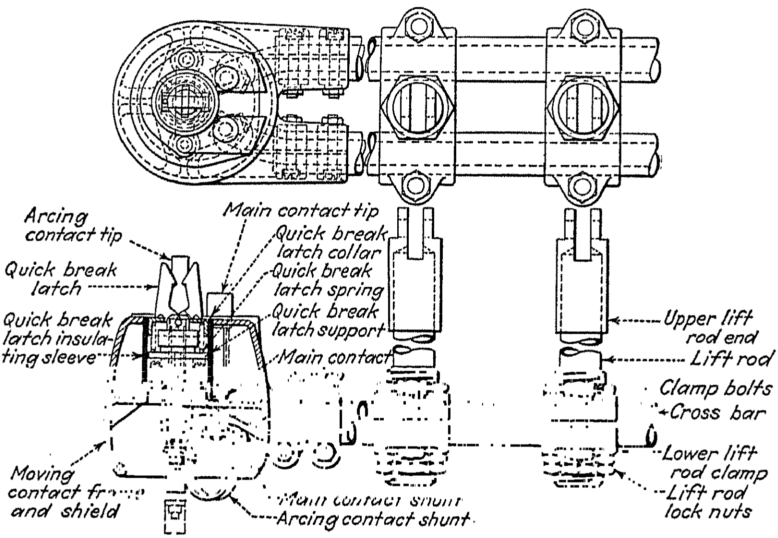


FIG. 34.—Details of moving member of Fig. 32.

it is used on circuits where the arc length will never be greater than the travel of the main contacts at the time the arcing tips part. If longer arcs are to be encountered, the arc will be reestablished between the stationary and moving contacts after the quick-break contacts have opened, and the switch will then be obliged to interrupt the circuit as a plain two-break breaker without the assistance of any accelerated break mechanism.

Bayonet-type high-speed contacts are used on the G–22 and G–22A from 110,000 volts up; the G–111, 110,000 volts; and the G–11, from 132,000 volts up. Both the main and

arcing contacts are of the butt type. The main contacts have short movement and are backed by heavy pressure springs. The high-speed element carries the arc tip and a hardened-steel finger which engages with a steel latch on the moving element. It is controlled by a compression spring, and a heavy shunt is provided to carry the current.

As the breaker opens, the main contacts are disengaged after about ½ in. of travel. The high-speed element moves downward, compressing the large spring above. It is automatically released at from one-third to one-half of the breaker travel and quickly returns to its normal position under the action of the spring. This is accomplished by rotating the latch tongue. A spiral slot is cut in the guide tube in which a pin rides. As the contacts open, the pin moves vertically downward for about one-half of the stroke and is then rotated, turning the latch tongue and disengaging it from the latch. This feature is shown in Fig. 33.

Lift Rods.

A recent outstanding achievement has been the development of wood-micarta lift rods. These lift rods are incorporated in all the type G line of breakers now being manufactured.

This new construction consists in cementing together, by the micarta process, sheets of selected wood veneer 0.05 in. thick and compressing them to one-half their original thickness under heat, which cures the micarta compound.

The resulting product is a material of great uniformity electrically and mechanically. It averages 10 per cent better than the best obtainable maple or 40 per cent better than the average maple or hardwood.

The use of this new material eliminates the uncertainty regarding the quality of the wood, as it does away with the objectionable cross-graining and sap streaks, which cannot always be detected in the natural state.

Wood-micarta is superior mechanically and electrically to any other material now available for this work.

In all type G breakers, space is provided for mounting bushing-type current transformers. When specified on order, the transformers come assembled in the breaker with all connections made and leads brought out for external connections.

The transformers are completely enclosed in steel cases in type G–10 breakers from 73,000 volts up. In the types G–22, G–222, and G–222A below 110,000 volts, the transformers are mounted in recesses in the casting and supported from below by a casting bolted in place, thus isolating the transformer from the interior of the breaker and forming a protection from the arc gases. The type G–22 breakers from 110,000 volts up have the transformers mounted in cast-steel cases. All internal wiring is protected from the arc gases either by putting it in conduit or by isolating it completely.

FIG. 35.—Westinghouse bushing-type current transformer.

Current transformers are mounted in the top of the pole units and may be single ratio, compensated for a given loading, or may be of the standard multiratio type. All leads are brought out and numbered for external connection.

Solenoid mechanisms are standard for the type G line of breakers and are mounted either on the end of the supporting frame or on the side of the first pole unit. The mechanism may be the non-automatic, or the full-automatic type. For the lower-capacity breaker, a mechanism with a 4-in. diameter core is supplied, and, on the larger-capacity breakers, the mechanism with a 6-in. diameter core is supplied.

The non-automatic solenoid mechanism consists essentially of a moving core operating on a main lever to close the circuit breaker, the main lever being retained in the

closed position by the trigger until tripped free by hand-trip device or the shunt-trip solenoid. The mechanism is equipped with an accelerating device to speed up the opening of the circuit breaker, and this accelerating device is provided with a dashpot, which retards the operation on the end of the opening stroke.

Operation.

When the control switch at a distant point is thrown to the position for closing the circuit breaker, current flows through the closing solenoid, drawing the moving closing core toward the stationary core. It is customary to use a control relay so that the current coming from the control switch to the electric mechanism will be only that necessary to operate the relay-switch coil, which, in turn, connects the solenoid coil to the control bus.

The mechanically full-automatic electric closing mechanism supplied for installations, where it is desired to close the circuit breaker from a distant point and, also, make it possible by mechanical means to hold the breaker in the closed position under predetermined conditions of overload on the line, is normally used on the complete line of G breakers.

Centrifugal-type motor mechanisms may be obtained on special order. The mechanisms are more fully described in the chapter devoted to Operating Mechanisms.

Condenser-bushing Potential Device.

As the name of the device implies, the condenser bushing is used to supply a source of potential. This is accomplished by providing a tap on the last metal-foil layer of the bushing, resulting, actually, in a condenser potentiometer. The device operates from the tap and is so designed that the normal function of the bushing is not interfered with in any manner. The tap is obtained by means of a rigid molded construction, and there is no danger whatsoever of trouble between the tap and ground developing through faulty

insulation. Since the condenser bushings are usually designed to have an approximate drop of 4,000 volts per layer, means must be provided for reducing the voltage to a value suitable for instrument use. A low-ratio indoor potential transformer is used for this purpose. In addition, an

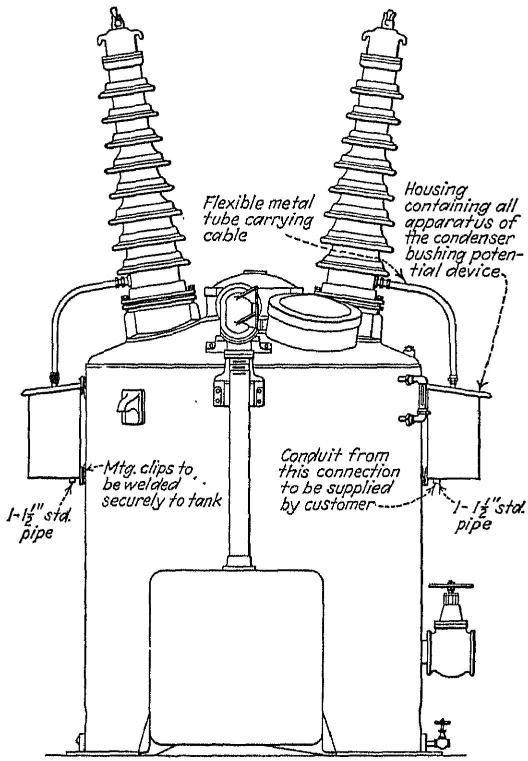


FIG. 36.—Assembly of potential device on Westinghouse oil circuit breaker.

impedance network is connected to the secondary of the potential transformer, permitting a more constant voltage ratio at the instrument terminals, regardless of variation of burden within the rating of the device.

Figure 36 illustrates the location of this device. Figure 37 indicates the schematic and vector diagrams and the equivalent circuit diagram.

The entire device excepting the instrument is assembled in a small protective sheet-steel housing and mounted on the circuit-breaker tank. The outstanding point to be noted is the simplicity of the device. It operates continuously without any attention to auxiliaries.

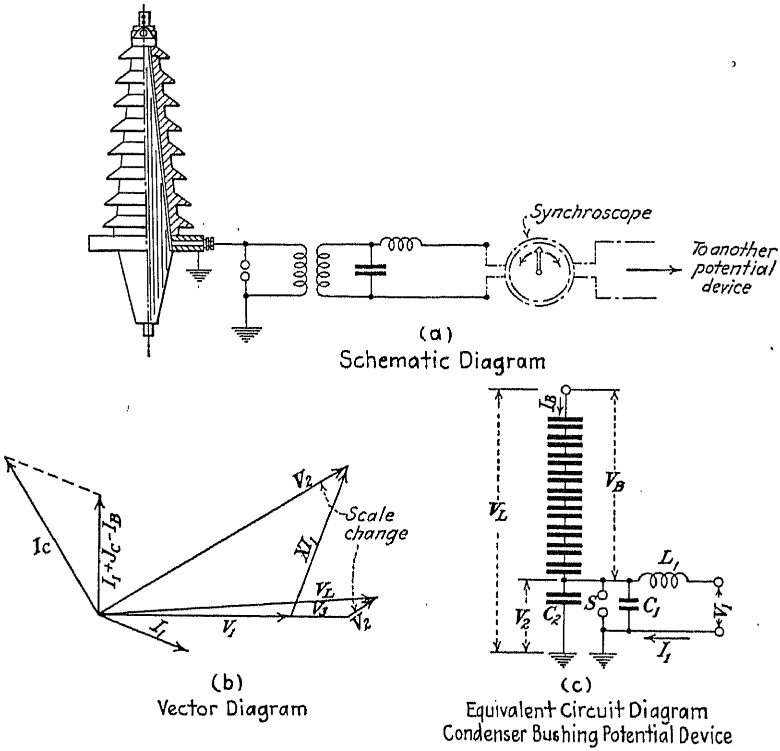


FIG. 37.—Circuit diagram of potential device shown in Fig. 36.

The secondary leads from the device are handled in the same manner as secondary leads from a potential transformer. One side of the equipment may be grounded, and, also, in case three-phase potential is desired, the secondary circuits may be connected in star.

The equipment within the housing consists of a spark-gap type of lighting arrester, low-voltage ratio-potential transformer, a reactor, and a condenser. To prevent excessive

voltages on the network due to overvoltages on the system or overloads on the network, a relief gap is supplied as part of the network. The operation of the spark gap is not continuous, however, and ceases as soon as the abnormal condition is removed due to the small currents involved.

The most favorable application of this device is for synchronizing at high voltage, thus originating the name "condenser-bushing synchronizing" equipment. The question of voltage regulation is not very important when operating a synchronoscope, and several degrees phase-angle error is permissible in the synchronizing operation. The voltage regulation as obtained with the condenser-bushing device is practically a straight-line variation. In addition, when synchronizing with the use of two identical potential devices, the phase-angle error cancels out. The use of a potential transformer on one line to be synchronized and a condenser-bushing synchronizing device on the other is not recommended. The application of this device should be limited to station layouts where it is permissible to use a condenser-bushing device on each of the lines to be synchronized. Under this condition, the maximum phase-angle differential that may be expected between any two condenser-bushing potential devices throughout the commercial frequency range (50 to 70 cycles) is 5 deg. This error is due to possible manufacturing variations within the synchronizing equipment itself and is designed to be practically zero at 60 cycles. This small variation in phase-angle error will not interfere with the usual synchronizing operation.

There are several other uses of the condenser-bushing potential device in addition to synchronizing. The same limitations with regard to phase-angle and voltage performances, as above mentioned, will apply here, also. In general, on applying this device, the maximum permissible burden must not be exceeded. Otherwise, the condenser bushing itself will be affected by increasing unduly the voltage across the tapped layer. Additional applications may be listed under three general headings:

1. The first is voltage indication. Under this application, it is to be noted that the condenser-bushing potential device can be used for giving an indication of voltage for use with voltmeters or the voltage element of indicating wattmeters but is not accurate enough for measuring power.

2. Probably one of the most important future applications of this device will be in the relay field. Due to the simplicity and economy as compared to voltage transformers, the use of relay schemes requiring potential should become more general. It may be used in place of voltage transformers for such relays as require potential, provided the phase-angle and regulation characteristics for the particular volt-ampere burden will not cause improper relay functioning. The secondary volt-ampere burden for bushing mentioned above must not be exceeded.

3. Another application is for frequency indication. Inasmuch as there is no frequency change within the condenser-bushing potential device, a true indication of frequency will be given.

Rating.

The apparatus committee of the National Electric Light Association has devoted much time to the consideration of oil circuit breaker rating and in December, 1923, adopted the following definitions and rules as a standard to be used in testing and comparing oil circuit breakers:

1. Interrupting rating is based upon the highest r.m.s. current at normal voltage which the oil circuit breaker can interrupt under the operating duty specified.

The value of current shall be taken during the first half cycle of arc between contacts during the opening stroke.

2. Operating duty shall consist of a definite number of unit operating cycles at stated intervals.

3. Each unit operating cycle shall consist of closing the circuit breaker followed immediately by the opening of the breaker (*i.e.*, without purposely delayed action).

4. The breaker shall perform its rated operating duty without emitting flame.

5. The condition of the circuit breaker shall be determined by an inspection and shall show:

   a. *Mechanical.*—Inspection shall show the breaker to be substantially in the same mechanical condition as at the beginning.

b. Electrical.—Inspection shall show the main current-carrying parts of the circuit breaker to be in substantially the same condition as at the beginning. However, the interrupting ability of the circuit breaker may be materially reduced.

The standard operating duty shall consist of two unit operating cycles at a 2-min. interval. [This is the so-called "OCO + OCO" duty cycle.]

TABLE IV.—RATINGS

Type	Rated volts	Rated amp.	Interrupting capacity at rated voltage	
			Amp.	Kva.
G-10	73,000	400, 600	1,200	150,000
G-22S	73,000	600, 1,200	4,000	500,000
G-222S	73,000	600, 1,200	8,000	1,000,000
G-222AS	73,000	600, 1,200	12,000	1,500,000
G-1	88,000	600	1,700	250,000
G-11S	88,000	600	2,600	400,000
G-22S	88,000	600, 1,200	6,500	1,000,000
G-10	110,000	600	1,300	250,000
G-111S	110,000	600	2,600	500,000
G-22S	110,000	600	5,500	1,000,000
G-222S	110,000	600	8,000	1,500,000
G-11S	132,000	600	3,300	750,000
G-22S	132,000	600	6,500	1,500,000
G-11S	154,000	600	2,800	750,000
G-22S	154,000	600	5,500	1,500,000
G-11S	187,000	600	3,100	1,000,000
G-22S	187,000	600	6,200	2,000,000
G-11S	187/220 kv.	600	3,300	1,250,000
G-22AS	187/220 kv.	600	6,600	2,500,000
G-11S	220,000	600	3,300	1,250,000
G-22S	220,000	600	6,600	2,500,000

THE DEION-GRID OIL CIRCUIT BREAKER

The Westinghouse Company recently announced a new and revolutionary development in the field of high-voltage oil circuit breakers. The announcement was contained in

two papers presented at the Midwinter Convention of the A.I.E.E., the first being by Dr. J. Slepian (43*a*), entitled "Extinction of a Long A.-C. Arc," and the second by B. P. Baker and H. M. Wilcox (43*b*), entitled "The Use of Oil in Arc Rupture." These papers should be consulted for the theory and application of this new principle.

In his investigation Dr. Slepian has found that, contrary to the usual opinion, the oil in the circuit breaker performs an important function in the extinction of the arc as well as being an insulating medium. When the contacts of the breaker part, an arc is struck, which breaks down some of the oil and produces the gas bubble which envelops the arc and the contacts. This gas bubble is made up of highly ionized material which reduces the gradient for arc extinction and permits a reestablishment of the arc after the current zero has been passed through. Dr. Slepian concludes that the extinction or reestablishment of an alternating-current arc in gases following a current zero is dependent principally on two factors: first, the rate at which the arc space recovers dielectric strength after current ceases to flow; and second, the rate at which the voltage applied to the arc terminals by the external circuit builds up. The second factor depends principally upon external circuit conditions and is therefore independent of breaker design. It remained to discover a method for increasing the rate of recovery of the dielectric strength in the arc space in order to decrease the arcing time and consequently increase the rupturing capacity of the breaker.

As stated above, the gas bubble is made up of highly ionized material and a de-ionizing agent will decrease conductivity by neutralizing the ionized particles. It was found that wherever the magnetic blowout effect was a factor in breaker operation, better results were achieved. At first this success was attributed to a lengthening of the arc although no very convincing theory had been advanced to explain the mechanism of the action. Dr. Slepian has concluded that the magnetic action forces the arc sidewise

against what may be described as the outer wall of the gas-filled area or "gas bubble," thus producing a supply of relatively cool, un-ionized gas which, dispersed throughout the arc space, acts as nuclei about which the recombination of ions takes place at a tremendously greater rate than would be possible in the hot gas of the arc stream alone. The

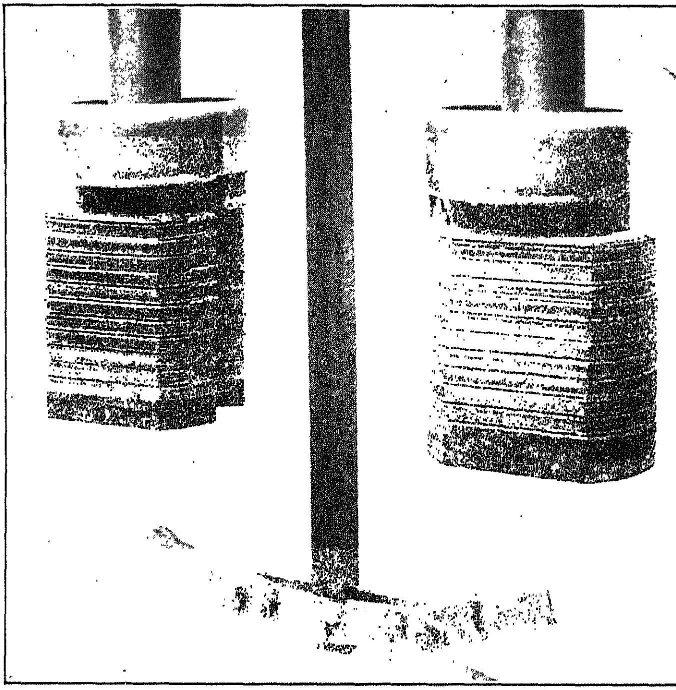


FIG. 37*a*.—Inside view of the oil circuit breaker equipped with deion grids.

practical application of this theory has led to the development of the deion-grid oil circuit breaker.

A view of the contacts of a breaker equipped with deion grids is shown in Fig. 37*a* and the details of the grid stack are shown in Figs. 37*b* and 37*c*. Each unit of the grid stack is built up of three different materials, the several elements being punched into the four shapes shown in Fig. 37*b*. The upper left-hand piece is of fiber; on top of this is placed the

lower right-hand horseshoe-shaped piece which is of iron and which is protected on the inside by the upper right-hand fiber piece, the assembly of these three pieces being illustrated in Fig. 37*c*. Complete insulation of the iron is obtained by placing on top of the three pieces thus assembled another of the fiber pieces of the first type. The unit is

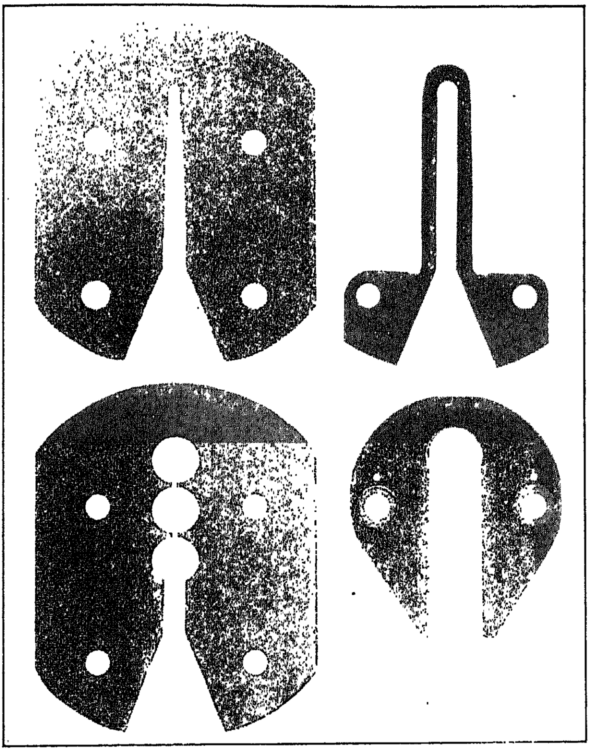


FIG. 37*b*.—The elements of iron, fibre and fullerboard used in building each unit of the deion grids.

completed by the addition of four of the fuller board punchings shown in the lower left-hand corner of Fig. 37*b*. Different numbers of these grid units are piled up for different voltage duties, the complete stack for a 110 kv. breaker consisting of 11 similar units held together by insulated bolts. The moving element of the switch contacts passes

through the slot just inside the tips of the iron horseshoe-shaped element.

The arc, being a conductor carrying current, is surrounded by a magnetic field, part of which is in the air gap across the iron, the balance being around the iron path.

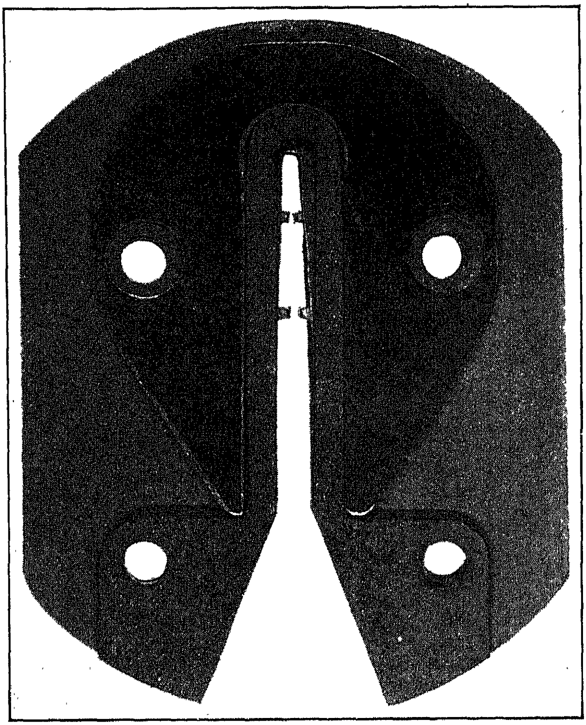


FIG. 37c.—An elemental group or unit of which the deion grids are made up, showing the arrangement of the iron and insulating materials.

The tendency for the magnetic field being to assume the path of least reluctance, it moves inward toward the tip of the groove sweeping the arc with it. It will be apparent that an arc moving toward the closed end of the groove is in effect being forced against a solid wall of oil throughout its entire length, resulting in a high rate of decomposition of the oil with an accompanying continuous and adequate sup-

ply of fresh un-ionized gas. This gas cannot escape except through the arc stream since the arc fills the open end of the groove. Due to the driving power behind the arc, the gas is forced to pass through the arc stream, diluting it with small volumes of un-ionized gas, while current is flowing, which act as de-ionizing surfaces after the current zero is reached. An additional de-ionizing effect is obtained from the sides of the groove where the arc impinges as it moves. The insulating plate elements in the grid are of absorbent material containing in their submerged condition considerable oil content. As the arc passes over the edges of these grid plates exposed in the sides of the groove, the heat forces this material to give off its oil which is also volatilized and thrown turbulently into the arc stream. This characteristic of giving off oil and creating a gas film along the edges of the plate elements also serves to protect them from burning under the heat of the arc.

At the time of writing (February, 1930) more than 2,000 tests have been made on breakers equipped with deion grids with currents ranging from 20 to 15,000 amp. and at voltages of from 13,000 to 220,000 r.m.s. across a single pair of contacts. A large number of tests were made at the Westinghouse factory, others were made on the systems of the Duquesnes Light and Power Company at 60 kv., the Alabama Power Company at 110 kv., and the Philadelphia Electric Company at 220 kv. The tests have indicated that the theory of the breaker is proved in practice.

The arc duration has been greatly reduced. In one series of 35 tests at 42 and 69 kv. the average arcing time was 1.8 cycles, and on another series of 50 short-circuit interruptions at the same voltages the average arc duration was 1.9 cycles, the minimum and maximum being 1.0 cycle and 3.5 cycles, respectively. The arc energy has been greatly reduced and from a curve obtained with tests at 38 kv. shows an average arc energy when interrupting currents up to 5,000 amp. of less than 100 kw.-sec. The arc energy is very nearly constant for any value of current

interrupted up to 4,500 amp. This is contrasted to a similar curve for the standard quick-break contacts wherein the arc energy varies from about 100 kw.-sec. when interrupting a few hundred amperes to more than 1,500 kw.-sc., when interrupting 4,500 amp.

Reducing the time of arcing and arc energy has greatly reduced the pressure inside the tanks and consequently the danger of tank rupture. It has also very materially reduced the oil pollution. In one set of 95 single-phase interrupting tests at currents ranging from 250 to 4,500 amp., the majority of which were in excess of 1,000 amp., and at voltages between 38 and 88 kv., the voltage gradient necessary to break down the oil was reduced from 28 kv. per $\frac{1}{10}$ in. before the tests to 25 kv. per $\frac{1}{10}$ in. after the tests. This slight deterioration of the oil, together with the small amount of burning of the arc-drawing members and the perfect condition of the grids, indicated that the breaker was still in condition for continued interrupting service.

Contrast the above with the oil in previous types of breakers after a relatively few severe short-circuit interruptions. It becomes so highly carbonized as to be unsuitable as an insulator and contact parts are so badly burned as to require maintenance and readjustment.

Requirements 1, 2, and 4 listed on page 294 as being necessary in an oil circuit breaker for use on high-voltage transmission systems seem to have been met in the deion-grid breaker, and further operating experience is awaited with much interest as the results of actual service conditions are made known.

CHAPTER X

GENERAL ELECTRIC HIGH-VOLTAGE OIL CIRCUIT BREAKERS

THE high-voltage oil circuit breakers of the General Electric Company may be grouped into two main classes, namely, oval-tank breakers and round-tank breakers. The former class is designated as type FK–136, and the latter class as type FK or FHK–139. Each type is, in turn, further classified in accordance with the details of its construction and rupturing capacity, so that the final type designation gives to the initiated a complete description of the breaker. For instance, a breaker may be designated as type FHKO–139–54B–F2. This is a type FK–139 breaker with type H or explosion-chamber contacts and suitable for outdoor service. The numerals 54 indicate a round tank 54 in. in diameter. The letter B represents the intermediate of three rupturing capacities, and F2 represents the type of terminal bushing. Until very recently, all breakers up to and including 73,000 volts were supplied with solid porcelain bushings designated by the letter S, and breakers for use at voltages of 88,000 volts and above were supplied with oil-filled bushings designated as F1, F2, etc. Present 50- and 73-kv. breakers are supplied with oil-filled bushings which have been designated as F50 and F73, respectively. Standard General Electric oil-filled bushings are suitable for installation at altitudes up to 4,000 ft. above sea level. Above 4,000 and up to 10,000 ft., bushings with higher upper parts are used, and the bushing nomenclature is given the suffix A, as F–73–A.

Typical modern General Electric high-voltage oil circuit breakers are shown in Figs. 38, 39, 40, and 41. Figures 38

and 39 are examples of the frame-mounted breakers, the former being a 73-kv. breaker and the latter a high rupturing-capacity, 88-kv. breaker, the largest frame-mounted breaker built by the General Electric Company. Figure 40 is a 132-kv., floor-mounted breaker. Figure 41 is a high-capac-

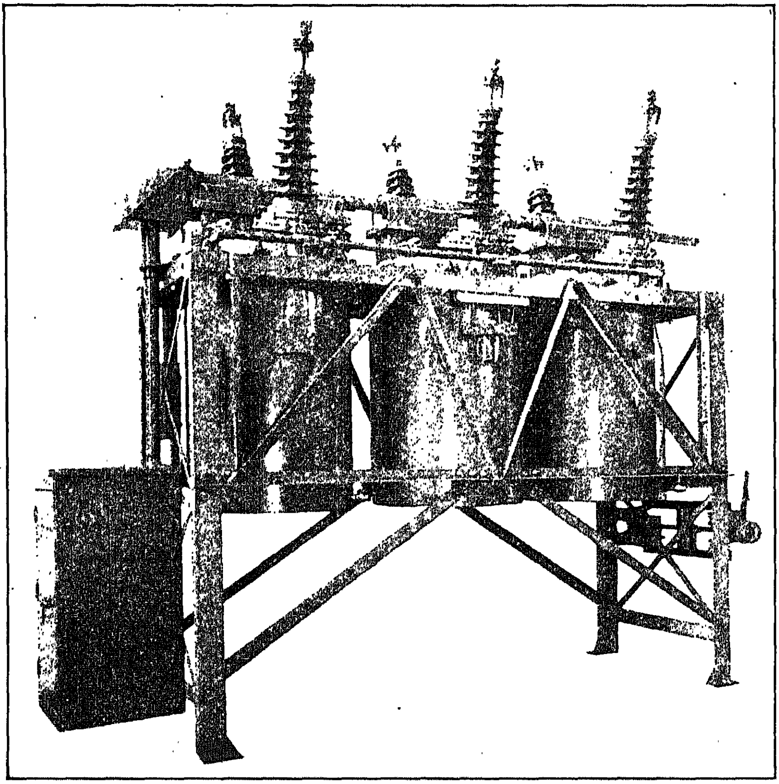


FIG. 38.—General Electric FHKO–139–42, F–73 oil circuit breaker.

ity, 187/220-kv. breaker for use on a grounded 220-kv. system.

The type FK–136 breakers for voltages up to and including 73,000 volts, and type FK–139 breakers up to and including 88,000 volts are designed for framework mounting. The framework is constructed of structural steel welded and bolted together to form a self-supporting structure suf-

ficiently high to raise the terminals beyond the reach of accidental contact and to permit the lowering and removal of the tanks (with contacts open) for purposes of inspection, repairs, etc.

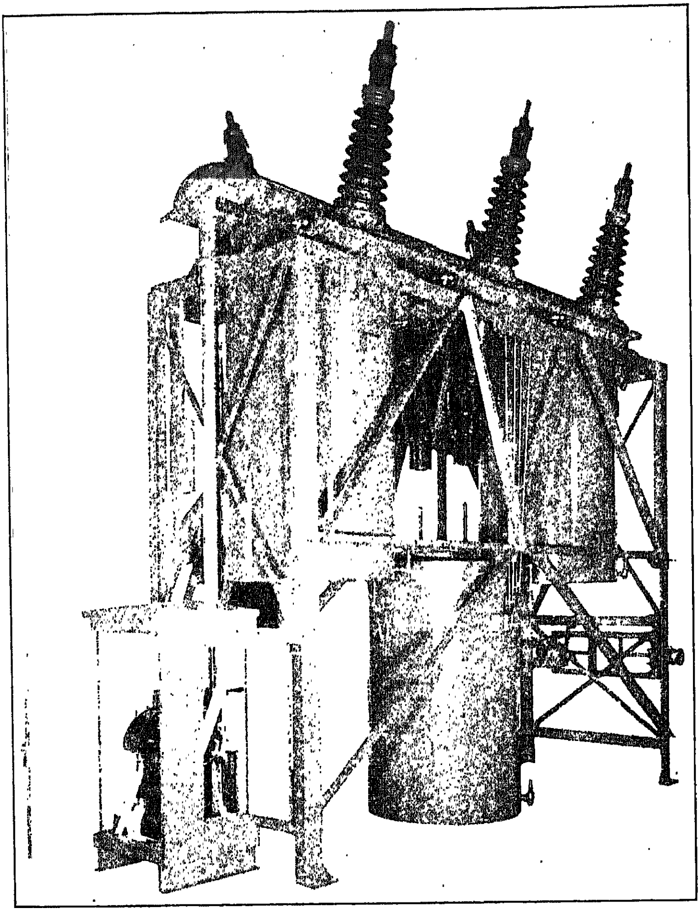


FIG. 39.—General Electric FHKO-139-48-B, F-1, 88-kv., 600-amp., frame-mounted oil circuit breaker.

For higher voltages the breakers are designed for floor mounting. All FHKO-139 breakers of the round-tank design have bumped bottoms, with the tank sides extending down beyond the bottom. Reinforcing bands are welded

at top and bottom, those at the bottom providing a means for anchoring the tanks to the foundations upon which they are set and the upper bands forming a collar with fittings for cover-clamping bolts. These breakers are provided with fabricated-steel domed covers designed to house bush-

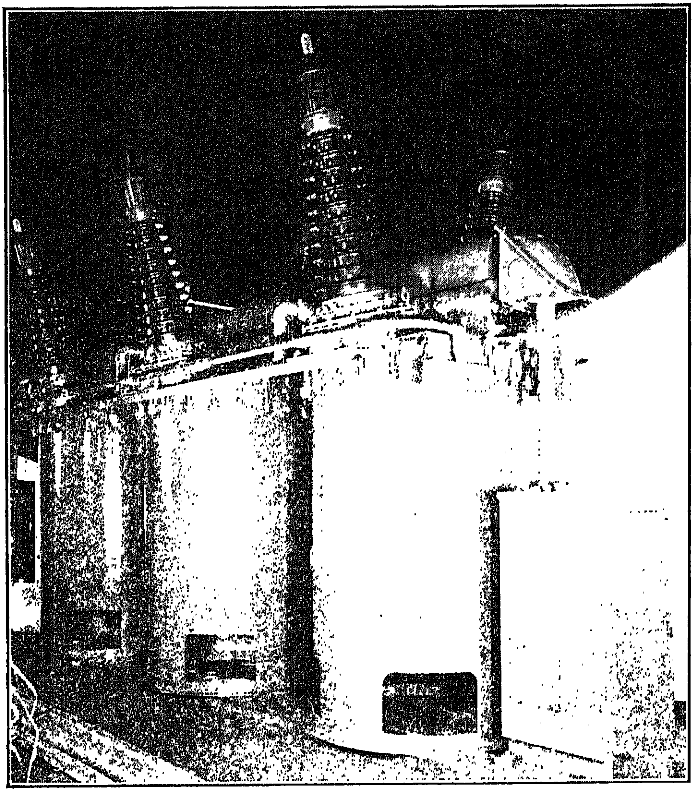


Fig. 40.—General Electric FHKO-139-60A-F-3, 132-kv., 600-amp. floor-mounted oil-circuit breaker.

ing-type current transformers and internal-operating mechanism. The fabricated-steel construction has proved stronger and more uniformly free from the possibility of oil leakage and hidden defects than was the case with the old cast-steel covers. All seams are double welded, with metal backing strips to insure an absolutely tight and rugged construction,

and tanks are tested to pressures greatly in excess of the maximum pressures for which they are rated.

Round-tank breakers have the clamping collar near the top of the tank, so that cover hold-down bolts will be of minimum length to insure the least possible elongation under severe short-circuit stresses, thus eliminating the possibility of oil throw.

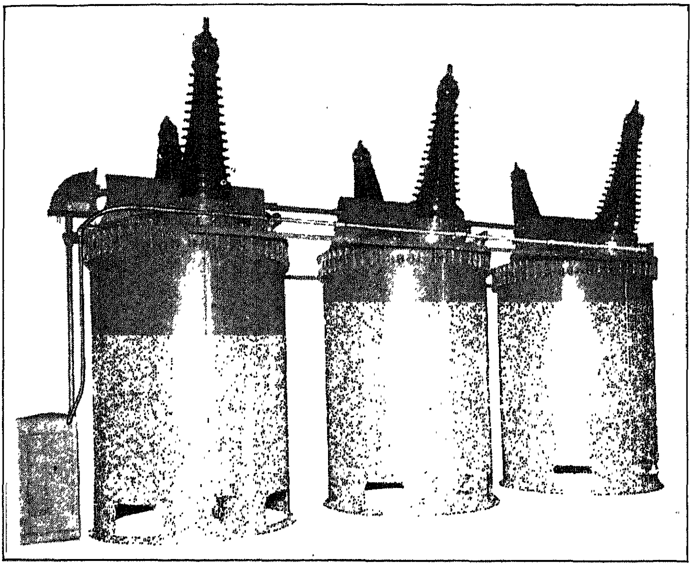


FIG. 41.—General Electric FHKO-139-108-Y.C, 600-amp., 220-kv. floor-mounted breaker operated by MK4 motor-operating mechanism.

All breakers of this class are provided with separating chambers with gas vents to care for expansion under rated interrupting duties. To care for abnormal pressures which might occur under conditions beyond the breaker ratings, emergency outlets are provided in the covers, designed to release below the pressures for which the tanks are designed and, thus, forestall any serious explosion which might rupture the tank with the consequent release of the insulating oil.

Floor-mounted breakers of the round-tank type are pro-

vided with manholes in the sides of the tanks on a line with and directly opposite the main contacts of the breaker. This greatly facilitates inspections and adjustments, especially in the medium-voltage breakers in which the tank size is such as greatly to cramp a man working inside the tank on contact maintenance.

The tanks of the breakers having relatively low rupturing-capacity ratings are oval in order to secure maximum clearance to ground and, at the same time, permit a minimum floor-space requirement. Bottoms are flat and tops are made of cast iron. Manholes are provided in the top casting. The bushings on all breakers for service at 50 kv. and above are of the oil-filled type. The upper section of the bushing is made of one piece of petticoated porcelain, except in the case of bushings for use on breakers for ratings of 187 and 220 kv., in which the upper section consists of porcelain shells joined together with metal clamping rings with a gasket between to make an oil-tight joint. In both cases, the bottom is cemented to a flange which is clamped to the bushing support. The lower section of the bushing is made up of one piece of petticoated porcelain cemented to a flange which is, in turn, clamped to the bushing support. The central section of the bushing where it passes through the cover of the oil circuit breaker is a metal tube flanged at each end to receive the flanges of the porcelain sections and, also, to afford a means for securing the bushing in place. This tube, also, serves to suppress any corona which might otherwise form on the small central conductor where it passes through the tank cover in close proximity to ground.

A copper tube extends through the center of the bushing, forming the conductor. The oil space between the center tube and the external shell is broken up into concentric ducts by insulating cylinders. The bushings are filled with the same grade of oil as is used in the breaker tanks. The top of the bushing takes the form of a glass gage, which gives a visual means of determining the level of oil in the bushings. Oil-filled bushings are designed to give a very regular voltage

gradient from line to ground and are especially adapted to withstand not only normal-frequency voltage surges but also high-impulse strains. Oil circuit breakers for 88 kv. and above can be furnished with bushings having capacitance taps for use with potential devices for metering and relaying. Bushings so equipped are approximately 4 in. higher than standard bushings.

Oil-filled bushings have given very satisfactory service, but two factors may be mentioned in connection with this type as compared with the condenser type of bushing. Being of porcelain and oil filled, they must be carefully watched for leaks, since their insulating value is destroyed if the oil is lost from the inside of the bushing. Also, they are less rugged than the condenser type of bushing, which is a built-up column of strong material. If an accident should break the protective porcelain housing of the condenser-type bushing, its insulating qualities are not impaired and the switch may be continued in service until repairs can be made. If, however, the porcelain of an oil-filled bushing is damaged to an extent which permits the escape of oil, the switch must be immediately taken out of service.

All FKO–136 breakers and FKO–139 breakers up to 110 kv. can be furnished either with direct-current solenoid-operated mechanisms or with alternating- or direct-current motor-operated mechanisms. FKO–139 breakers for 110 kv. and above are furnished standard with motor-operated mechanisms. Weatherproof housings are provided for the mechanisms and auxiliaries of all outdoor breakers. These are constructed so as to permit accessibility to equipment. Holes are provided in the case through which the conduits for the control circuits may be run. Cover pipes are provided over the operating rods, making them waterproof. The essential difference between the FK–136 and the FK–139 breakers lies in the breaker machanism, which is mounted on the top of the breakers and connects the several poles to operate the contacts. In the case of the FK–136 breaker shown in Fig. 42, this mechanism is outside the tank and is

mounted so that it can be removed without disturbing any other part of the breaker. Being outside the tank, the operating rod is subjected to unequal pressure—on the one

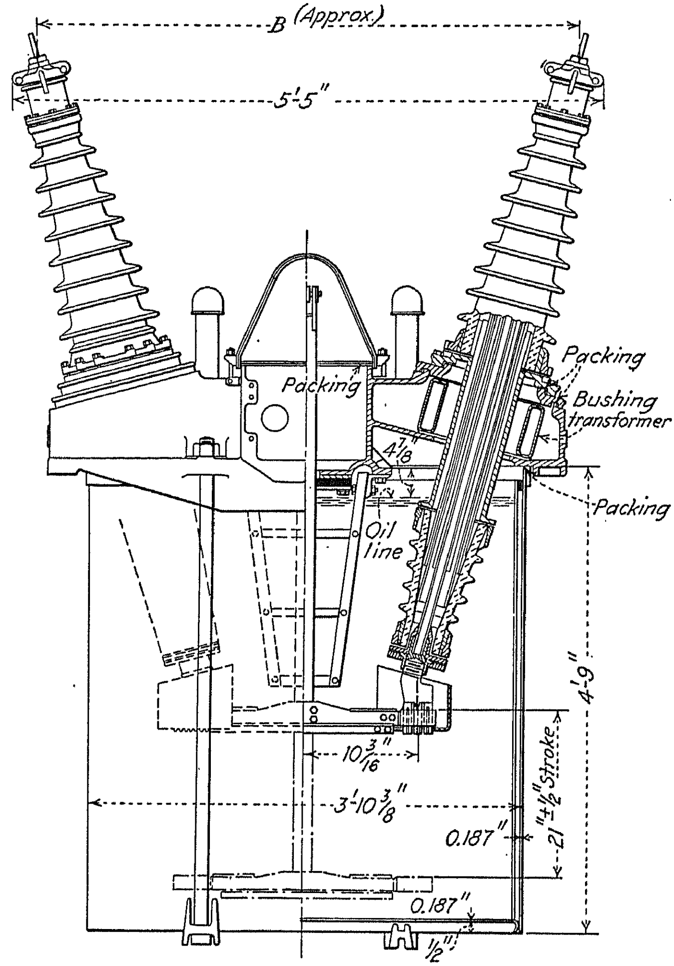


FIG. 42.—FKO-136-2046A-F-73 oil circuit breaker contacts and bushing details.

hand, atmospheric pressure and, inside the tank, the pressure generated by the action of the arc. This difference of pressure acts against the opening motion of the breaker contacts and, in some cases, may cause a slowing down of

breaker action. The breaker is not rated, however, for high interrupting capacity, and accessibility for inspection and adjustment together with less expensive construction makes this type of mechanism suitable for this class of breaker.

The type FK–139 breakers shown in Fig. 43 have their connecting mechanisms mounted in chambers formed in the cover which are connected directly with the oil tank. In this case, any pressure which is developed by the arc is equalized on all sides of the mechanism and operating rods, and there is no tendency to slow down the operation of the breaker. The operating rods connecting the several poles of the breaker pass through stuffing boxes, and there is no connection between the tanks and the different phases whereby gas generated in one pole may be passed on to another pole. The rods for the operation of contacts are all arranged in such a manner as to be under tension when operating the breaker. This is a decided improvement over the old push-rod type of mechanism.

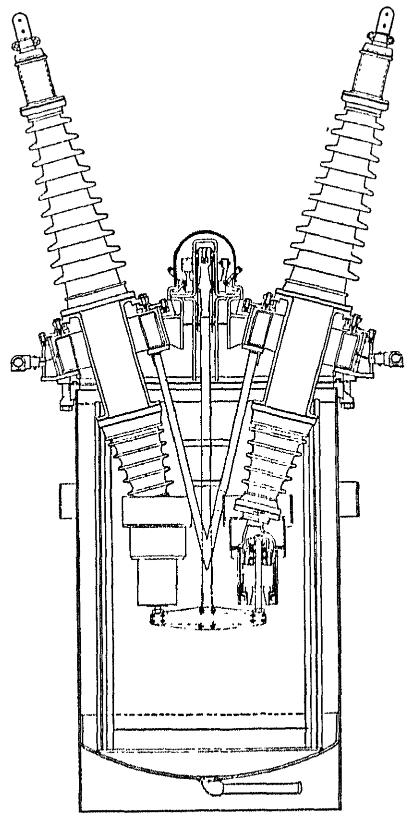


Fig. 43.—FHKO–139–48B–F–1 assembly.

Contacts.

Two types of contacts are used on the high-voltage oil circuit breakers of the General Electric Company, namely, the wedge-and-finger type, shown on the FK–136 breaker

in Fig. 42, and the explosion-chamber type, shown on the FK–139 breaker in Fig. 43. The breakers with the lower, or A, rating of interrupting capacity are equipped with the wedge-and-finger type of contacts and operate as plain-break breakers without any auxiliary secondary contacts to aid in speeding up the break. The stationary contacts consist of flared drop-forged copper fingers secured to a contact block fastened on the end of the conductor passing through the bushing. The flared fingers assist as guides to the entering blade as well as form the arcing tips to relieve the main contact surfaces from pitting and burning. The movable contacts consist of wedge-shaped copper contacts mounted on each end of a wooden crosshead and joined together by secondary copper connectors. The wooden crosshead is attached to a movable treated wooden operating rod. The breaker opens by gravity assisted by accelerating springs on the operating mechanism. This type of construction employing a plain break with no auxiliary device for increasing the speed of the break is suitable only for relatively low interrupting capacities, and such breakers cannot be used on large transmission networks or in stations where rupturing duties of the order of 500,000 kva. or over may be encountered. These breakers have a maximum rating of 500,000 kva.

For the intermediate and high rupturing capacities (B and C), the General Electric Company uses the type H or explosion-chamber contact to secure an accelerated break. Breakers rated with a carrying capacity above 600 amp. have additional primary contacts which break before and make after the secondary contacts. The primary contacts consist of stationary laminated strip brushes of the inverted or reversed type, so that mechanical stresses due to heavy current will increase contact pressure. The movable primary contact consists of copper blades attached to the operating rod above the crosshead which carries the movable secondary contact rods. The blades close into the brushes with a wiping contact, slightly spreading the laminations.

The secondary contacts consist of heavy movable copper rods with removable brass arcing tips and are clamped at the ends of the crosshead, which is clamped at its center to the unit operating rod. The contact rods make plunger contacts with sets of stationary segmental contacts mounted on the contact retainers in the upper ends of the explosion

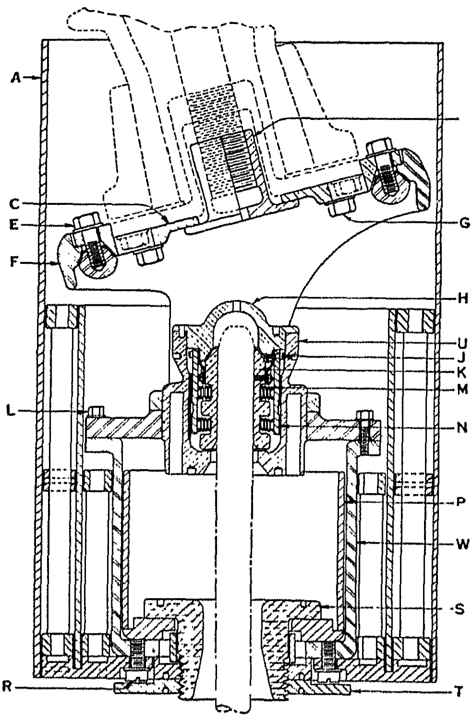


FIG. 44.—Explosion-pot details for General Electric breakers of 110-, 88-, and 73-kv.

chambers. The details of the explosion chamber and contacts for use on breakers rated at 73, 88, and 110 kv. are shown in Fig. 44. The stationary contacts consist of hollow cylinders made up of vertical segments *K* each held in place by two short, heavy compression springs *M*, which, in turn, bear against a steel strap *N*. Each of the cylindrical segments is electrically connected to the top member *H* by a flexible copper strap.

For voltages of 132 kv. and above, the type FHKO–139 breakers are furnished with a newly developed non-metallic explosion chamber, as shown in Fig. 45 for 132- and 154-kv. breakers and Fig. 46 for 187- and 220-kv. breakers. It was found that on breakers for these higher-voltages duties, very high-voltage peaks were possible at times of system dis-

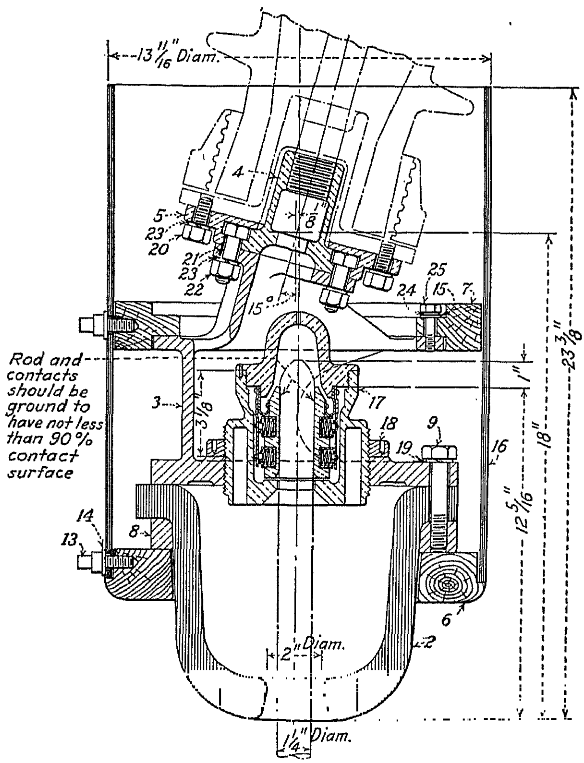


FIG. 45.—Details of General Electric explosion pot for 132- and 154-kv. breakers.

turbance, which might cause internal trouble on breakers designed with the recognized standard clearances. The breakers have, accordingly, been redesigned, and an explosion chamber made of herkolite was developed to give increased insulation. In addition to being non-metallic, these herkolite chambers are extremely rugged in construction and will withstand very high explosion pressures.

The operation of the explosion chamber contact is as follows: When the breaker is opened, an arc is established between the stationary and movable contacts. Contact of the arc with the oil generates gases which develop a high pressure within the explosion chambers. This pressure com-

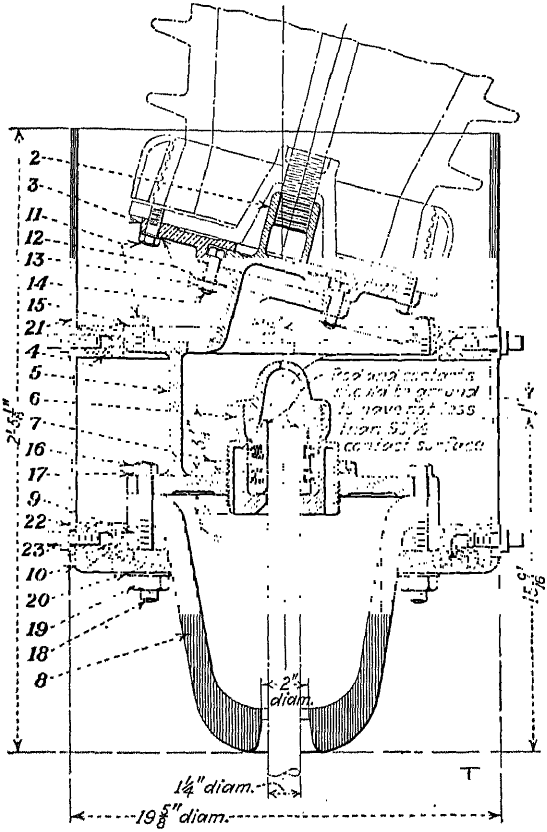


FIG. 46.—Details of General Electric explosion pots for 187- and 220-kv. breakers.

presses the gases and, also, forces oil into the arc stream, giving a jet action to assist in extinguishing the arc. This pressure, also, tends to eject the contact rods, thus assisting the acceleration of the opening of the breaker.

As has been previously pointed out in the theory and discussion of high-voltage oil circuit breakers, the explosion-

chamber type of contact has many of the characteristics of a magnetic blowout, in that increasing current will cause a more rapid generation of gas and, consequently, increase the pressures developed and cause a more rapid break. The acceleration of the bayonet contacts is controlled by the clearance between the bayonet and the insulating bushing S (Fig. 44), the smaller the clearance the more pressure which can be built up in a given time and, consequently, the more force which will be available for ejecting the contacts. In the case of the type FHKO–139–42C–F73 breaker rated at 73,000 volts and with a normal continuous current-carrying capacity of 600 amp., the published rupturing capacity is 12,000 amp., a ratio of 20 : 1 between rupturing and carrying capacity. This means that clearances must be so proportioned that they will not be so small as to build up dangerous pressures when interrupting currents at the rated rupturing capacity, and yet be small enough when interrupting currents of a few hundred amperes to be of value in accelerating the break. This is a large order to meet, and a compromise must be accepted which will result in slower action under low-current duties than at maximum rating.

The argument is advanced that low-current values are more easily interrupted than high currents, but this is not always the case. It may, at times, be necessary to interrupt the charging current of a long extra-high-voltage transmission line on the low side of the transformers. This relatively low current at practically zero power factor, leading, produces an exceedingly stubborn arc to break, and the arc length may approach that encountered when rupturing fault currents approaching the rated interrupting capacity of the breaker. For this reason, the use of the explosion-chamber type of breaker for the control of transmission networks may be open to question. High speed of break is essential to the successful operation of a transmission network, and a gravity-operated breaker, even when assisted by accelerating springs and explosion contacts, will not give the highest possible speed of break.

TABLE V.—RATINGS [1]

Type	Rated volts	Rated amp.	Interrupting capacity at rated voltage	
			Amp.	Kva.
	Frame mounted			
FKO -136-2046A F73.....	73,000	400, 800	1,200	150,000
FKO -139- 42A F73.....	73,000	600, 1,200	4,000	500,000
FHKO-139- 42B F73.....	73,000	600, 1,200	8,000	1,000,000
FHKO-139- 42C F73.....	73,000	600, 1,200	12,000	1,500,000
FKO -139- 48A F1......	88,000	600	3,300	500,000
FHKO-139- 48B F1......	88,000	600	6,500	1,000,000
	Floor mounted			
FKO -136-2852A F1......	88,000	800	1,650	250,000
FHKO-139- 54C F1......	88,000	600, 1,200	10,000	1,500,000
FKO -136-3258A F2......	110,000	800	1,300	250,000
FKO -139- 54A F2......	110,000	600	2,600	500,000
FHKO-139- 54B F2......	110,000	600	5,500	1,000,000
FHKO-139- 60C F2......	110,000	600	8,000	1,500,000
FKO -139- 60A F3......	132,000	600	3,300	750,000
FHKO-139- 60B F3......	132,000	600	6,500	1,500,000
FHKO-139- 72C F3......	132,000	600	11,000	2,500,000
FKO -130- 72A F4......	154,000	600	2,800	750,000
FHKO-139- 72B F4......	154,000	600	5,500	1,500,000
FHKO-139- 78C F4......	154,000	600	9,400	2,500,000
FHKO-139- 90C F6......	187,000	600	6,200	2,000,000
FHKO-139- 96YB F6......	187/200	600		
FKO -139- 108YA F6......	187/220	600		1,250,000
FHKO-139- 108YC F6......	187/220	600	6,600	2,500,000
FKO -139- 108A F7......	220,000	600	....	1,250,000
FHKO-139- 108C F7......	220,000	600	....	2,500,000

[1] See rules on page 110.

GENERAL ELECTRIC HIGH-SPEED OIL CIRCUIT BREAKERS

The 220-kv. transmission lines of the Philadelphia Electric Company connecting Conowingo Power House with Siegfried Substation transmit 252,000 kw. from the generators into the system of the power company. These lines are only some 60 miles in length, but during the first summer's

operation a total of three flashovers was experienced, all involving two, or possibly three, conductors. The slow-speed, water-wheel driven generators at Conowingo ran out of step very rapidly and were so far ahead of the steam generators before the fault was cleared that they would not pull back into synchronism. They continued to run out of step until either their overspeed devices or the large synchronizing current over the sound line automatically disconnected them. Conclusions were reached that under this condition the solution of the problem would, in all probability, lie in the use of high-speed circuit breakers which would isolate the fault before the generators could advance far enough to pull out of step.

The General Electric Company set to work to modify the design of their breakers and built a single-pole unit which was subjected to 27 short-circuit tests at Plymouth Meeting Substation. The results of these tests are given in an article by Robert Paxton (43C) published in the *Electrical World* for Oct. 12, 1929.

In any oil circuit breaker the time of operation naturally breaks up into three parts:

1. The time required to disengage the trip mechanism and start the breaker in motion.
2. The time measured from the start of motion to the time when the arcing contacts part.
3. The time from parting of the arcing contacts until the circuit is interrupted.

The time from the parting of the contacts to the full open position of the breaker is not a constant quantity for explosion-chamber breakers, but varies with increasing current due to the increased pressure in the explosion chamber. On moderate-voltage circuits under full interrupting duty the time from parting of contacts until fully opened averages approximately 40 per cent of the no-load time, while for higher voltages this ratio varies between 50 and 60 per cent.

In order to decrease the time of the first and third item, the oil circuit breaker was provided with an opening mechan-

ism of very high speed. In order to decrease the value of the second item, new butt-type line contacts were developed. With this type of breaker the time from energizing the trip coil until the parting of the contacts was reduced to 5 cycles (on a 60-cycle basis).

The new type of butt-contact explosion chamber is illustrated in Fig. 46*a* and should be compared with the type

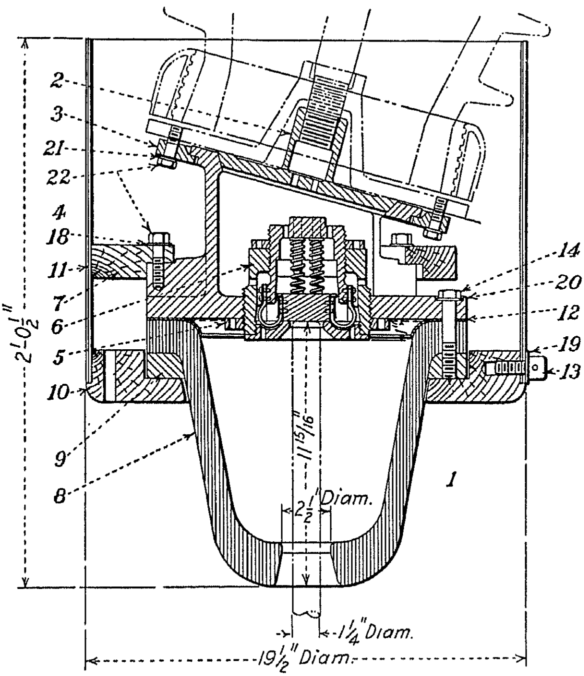


FIG. 46*a*.—Details of General Electric explosion pots with butt contacts for extra high-speed breakers.

shown in Fig. 46. It opens the metallic circuit after a fraction of an inch of travel, just sufficient to compensate for the slight movement of the back-up springs on the stationary butt-contact member. The older type required about 4 in. travel of the bayonet before it was completely withdrawn from the contact sleeve. With the mechanism starting from rest, this 4 in. of travel represented a considerable time before actual interruption of the arc could begin and, also, maintained

the short circuit on the transmission system a corresponding period. When it is considered that the maximum time a short circuit can be safely carried on a transmission line without causing loss of synchronism is approximately 12 cycles, it will be appreciated that this new contact has aided materially from the standpoint of increasing system stability.

Details of the new General Electric trip-free solenoid mechanism designed for the Conowingo tests are not available except as to operating currents. For a 110-kv. high-speed breaker designed for an operating time of 8 cycles, the solenoid requires a closing current of 350 amp. at 125 volts. The trip coil requires 10 amp. at 125 volts.

Operating and maintenance experience with the new contact mechanism will be awaited with considerable interest. The speed of breaker operation has been materially increased, but the theory of the explosion chamber requires the continuance of the arc until the bayonet has been withdrawn from the explosion chamber. The arc will be struck between the flat surfaces of the butt contacts, which are unprotected by any arcing contacts, and it may be that this will result in contact burning which will require considerable maintenance work to keep the breaker in condition to carry normal current. Some types of switch contacts carry currents to the order of two or three thousand amperes with a line or point contact (Railway and Industrial Engineering Company air-break switches), but this is done with tremendous contact pressures. Spring pressures in the butt contacts of the General Electric breaker are not known, but they are certainly much less than in the air-break switch referred to. A bead of copper on the butt-contact surface may possibly tend to cause local heating. Actual experience in service will be necessary to determine the merits of this type of contact.

The table of ratings given on page 141 is for breakers built with the older rod-and-segment or wedge-and-finger type of contacts and does not include any ratings for the new butt-contact breakers.

CHAPTER XI

PACIFIC ELECTRIC MANUFACTURING CORPORATION

The Pacific Electric Manufacturing Corporation breakers are distinguished from the usual types by being built on the rotary horizontal-break principle, a development of the original Sterling, and, later, Stanley, type of breakers described in the historical section of the text. Their claims of superiority are based on their better mechanical construction and use of fewer, more rugged parts and on the natural tendency of the gas bubbles around the arc to separate from the contacts as they move up through the oil in an area away from the supporting bushings.

This type of breaker requires positive mechanical action both in opening and in closing, as opposed to the gravity and accelerating-spring drop-bar type. The result has been a breaker in which all of the major adjustments are in the actuating mechanism and in the development of a very powerful and very positive actuating mechanism.

Since this type was originally devised by power-company engineers, that source of information has been freely used in its subsequent development, and because of the fact that the manufacturers of this breaker produce only high-tension switching equipment, changes were more readily carried out when changing conditions demanded different characteristics.

Early in its development, the multibreak principle was adopted for all of the standard breakers of the high-duty class, because its form of construction was particularly adapted to multibreaks without extra insulation to ground.

The present-day high-voltage breakers are nearly all six break, as shown in Figs. 47 and 48, where, as noted above, no more major insulation is required between the conducting

parts and ground than in the two-break breaker shown in Fig. 49, the additional breaks being insulated from each other by insulation adequate for that duty but not subject to sustained dielectric stresses. The insulation which separates the auxiliary blades and contacts is of bakelite, rein-

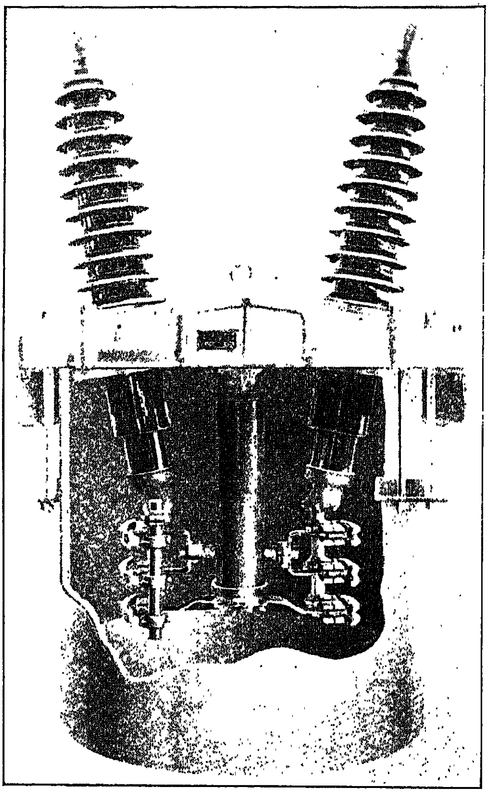


FIG. 47.—Pacific Electric Manufacturing Corporation R-45 six-break, 73-kv. oil circuit breaker.

forced internally with steel, and should it be punctured or otherwise fail electrically, the mechanical strength and alignment of parts would not be impaired and the failure would result only in the cutting out of two or more breaks in the circuit.

When the circuit breaker is closed, the insulation between

the groups of contacts is not under electrical stress, because all parts that it supports are connected together. When the breaker is open, this insulation is also free of stress because the parts are entirely disconnected and outside the path of possible electrostatic leakage. It is only during the few cycles between the opening of the breaker and the rupturing of the arc that this bakelite insulation is subject to dielectric stress.

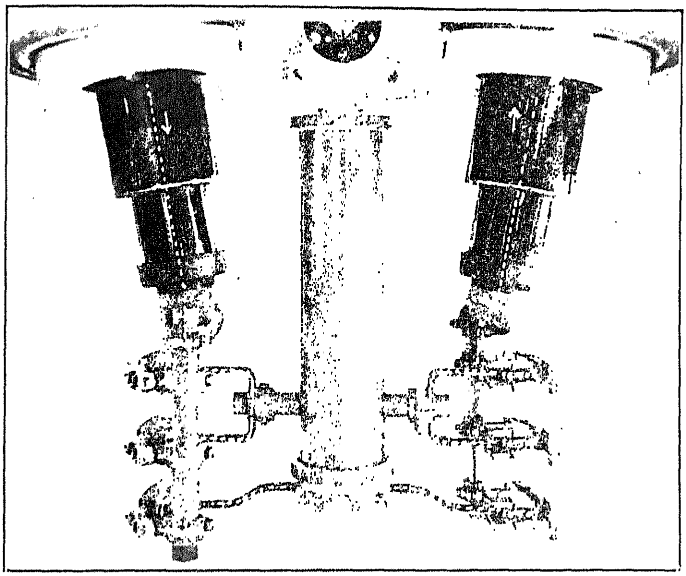


FIG. 48.—Pacific Electric type R-45, 400-amp., 73-kv. oil circuit breaker showing current path.

The fixed contacts are supported by the entrance bushings. The contact shoes are self-aligning and are pressed against the blades by springs which do not act as conductors, conductivity being furnished by flexible copper shunts riveted to the shoes. These contacts are readily accessible for inspection and repairs, and, as they are self-aligning, their initial adjustment is simple and easy.

Modern representatives of this manufacturer's product have the contacts electrostatically shielded with smooth

metal surfaces in order to take advantage of the additional safety from flashover to the tank when all bolts, nuts, and sharp corners are covered with smooth rounded shields.

The blades are suspended by and rotate with a bakelite tube of generous proportions in the newer types or on porcelain insulators in the older models. The entire rotating element is carried on antifriction bearings, Timken in the larger sizes. Power is supplied to rotate these elements

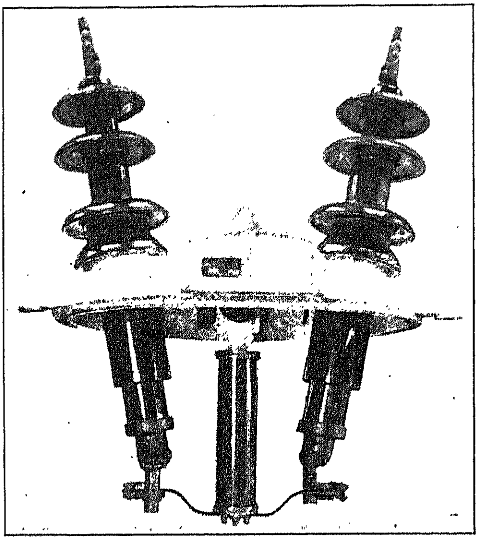


FIG. 49.—Pacific Electric type JB–45, 400-amp., 73-kv. oil circuit breaker equipped with bakelite rotating unit.

by sectors of bevel gears driven from a horizontal shaft through the top of the three tanks and coupled direct to the operating mechanism through flexible couplings made up of steel discs between each tank to insure proper alignment at all times.

Since the blades float freely in the self-aligning contacts, no stops are required, as the operating mechanism supplies all that is needed. On the heavier breakers, oil dashpots similar in action to popular automobile shock absorbers are placed in the rotating element under the oil level.

Tanks.

The tanks used are all of welded boiler plate of round section with bumped bottoms. Those of 73 kv., and below, have cast-steel tops with a machined groove filled with flax packing for the tank tops. Tops and tanks are bolted together with short bolts entering an angle-iron band near the top of the tanks.

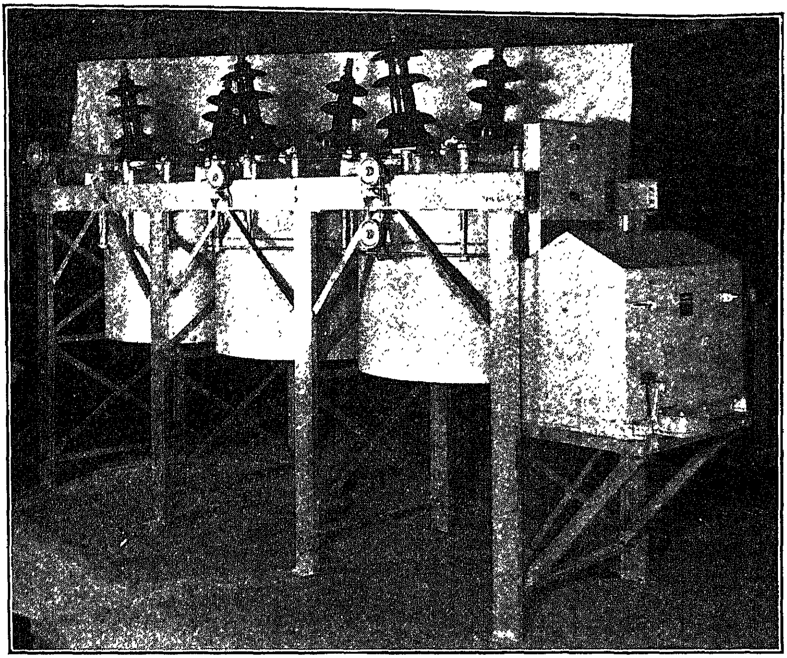


FIG. 50.—Pacific Electric R–45, 73-kv., frame-mounted breaker with motor-wound spring-type operator.

These breakers are all frame mounted on galvanized frames, as shown in Fig. 50.

The floor-mounted breakers 115 kv., and above, are being changed at present (1929) to welded boiler-plate tanks and fabricated tops to produce a welded structure shown in the outline drawing (Fig. 51) and their ratings as shown in the table on page 153.

Bushings.

Frame-mounted breakers have solid porcelain bushings of either Ohio Brass or Locke manufacture, as described

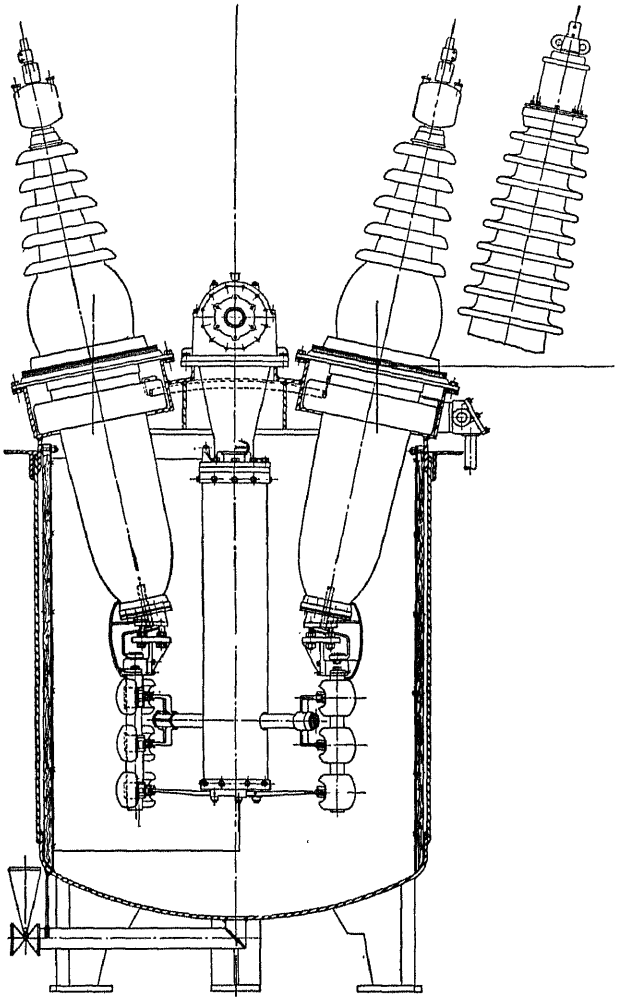


FIG. 51.—Pacific Electric floor-mounted breaker details. (Note electrostatic shields on contacts.)

under the Chapter on Bushings. All of the floor-mounted breakers are equipped with oil filled bushings of either Ohio

Brass or Locke manufacture, allowing some choice in characteristics.

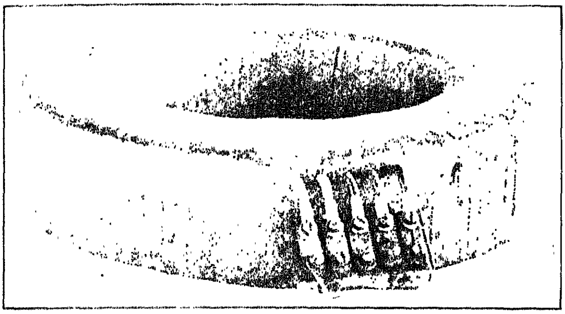


FIG. 52.—Pacific Electric bushing-type current transformer.

Current Transformers.

In addition to the usual bushing type (see Fig. 52) current transformers common to all manufacturers, the Pacific Electric Manufacturing Corporation furnishes wound-type

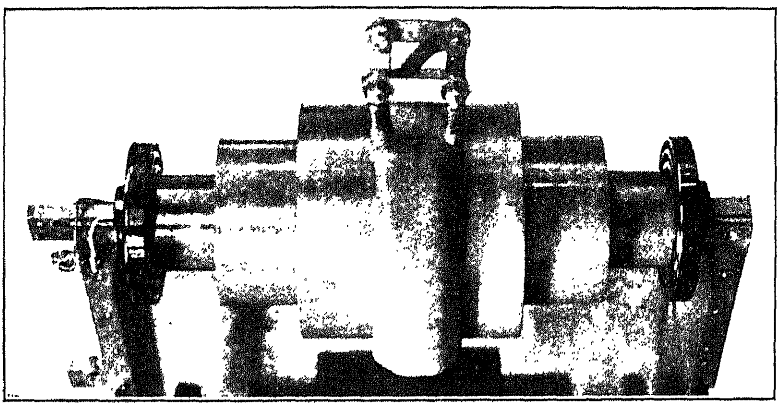


FIG. 53.—Pacific Electric wound-type current transformer for 132 kv., used inside breaker tank.

current transformers similar to the conventional metering transformers but mounted inside the oil circuit breakers.

Such a transformer for 132-kv. service is illustrated in Fig. 53. These transformers may be wound for low ratios.

giving results equivalent to instrument transformers without the expense of the tanks and bushings normally required (71).

Operating Mechanism.

This company furnishes both solenoid and motor-wound spring-actuated mechanisms. The solenoids close the breakers and, at the same time, compress an opening spring which must possess sufficient energy to completely open the breakers when released. Speed curves for such a solenoid are shown in the chapter devoted to operating mechanisms.

The motor-wound spring-actuated mechanisms made by this company and designated as type MW, with a suffix denoting the size, have most of the features desirable in an oil circuit breaker operator. Essentially, the operator consists of two heavy helical compression springs which are compressed by a small motor and locked by toggles.

When the springs are fully compressed and locked, the operator is ready for its cycle of operations. When the control switch completes the circuit for closing the breaker, one of the springs is released and the breaker responds instantly, due to the very great strength of the spring. Similarly, when the breaker is to be tripped, the second spring is released and an exceptionally rapid travel is imparted to the moving switch blades. As soon as the second spring has tripped, the motor automatically recompresses both springs and sets the operator for the next cycle of operations. This compressing action consumes a maximum of 20 sec., which is not of serious consequence, because it is rarely, if ever, necessary to reclose a high-voltage oil circuit breaker in less than $\frac{1}{2}$ min. after it has been tripped.

By the use of two independent springs, one for closing and one for tripping, a perfect trip-free operation is obtained, for it is possible to release the opening spring at any instant and cause the blades to return to the open position from whatever position they may be in at that time. By using compression springs in place of tension springs, the danger of failure to operate due to a broken spring is removed,

since a broken compression spring will collapse only one turn and still have sufficient energy stored to operate the breaker. By using a small motor to compress the springs and gearing it so as to require approximately 20 sec. maximum or an average of 10 sec. to complete the operation, two things are accomplished: First, a considerable amount of energy may be stored in the springs with a relatively small motor, and, therefore, a large force is available instantly to open or close the breaker. Second, the control wiring and storage battery for the operation of the motor can be kept very small, the motor requiring only a few amperes as against a hundred or more amperes required by the centrifugal motor mechanisms which operate the breakers directly without the aid of springs, or several hundred amperes which may be required by the solenoid operators to give an equally quick closing stroke. The type MW operator is a relatively recent development and has been described in considerable detail in the *Electrical World* (43*d*). An additional advantage of this type operator is that considerable excess energy may be used without shock to the breaker mechanism because of the natural stops in the linkage employed when the toggles straighten out and lock.

TABLE VI—RATINGS

Type	Kv.	Amp.	Capacity, kva.	Total Break, in.	Gallons, oil
RW-52........	115	600	500,000	52	2,100
RW-58........	115	600	1,000,000	74	2,500
RW-64........	115	600	1,500,000	91	3,100
RW-64........	138	600	750,000	52	3,350
RW-72........	138	600	1,500,000	81	4,250
RW-78........	138	600	2,500,000	113	5,250
RW-72........	161	600	750,000	74	4,800
RW-78........	161	600	1,500,000	92	5,500
RW-84........	161	600	2,500,000	113	6,600
RW-108.......	191	600	2,500,000	147	13,200
RW-120.......	230	600	2,500,000	147	18,600

CHAPTER XII

KELMAN HIGH-VOLTAGE CIRCUIT BREAKERS

To the president of the Kelman Electric and Manufacturing Company, J. N. Kelman, is due the honor of having constructed the first oil circuit breaker for use on a 60,000-volt transmission line. In the 28 years that have elapsed since that time, he has been continually associated with the electric-power industry and has developed a high-tension oil circuit breaker which is unique and unlike any other high-voltage oil circuit breaker on the market.

An installation of Kelman breakers, which in general external appearance do not differ greatly from other high-voltage breakers, is shown in Fig. 61. All voltage ratings have round tanks of welded-steel plate with convex tops and bottoms formed from steel plate and welded in place. The tank material varies in thickness according to the rated interrupting capacity of the circuit breakers. The types 2D6A 70,000-, 3D6A 120,000-, and 12D6A 132,000-volt breakers are thus furnished with tanks made of $\frac{1}{4}$-, $\frac{3}{8}$-, $\frac{1}{2}$-, or $\frac{5}{8}$-in. plate. The 5D6A and 9D6A 70,000-volt breakers are furnished with tanks made from $\frac{5}{8}$-in. boiler plate. As the strength of the tank is increased, stronger entrance bushings are used to balance the resistance of the whole structure to withstand internal pressure. A manhole is provided in the top of the tanks to permit access for the inspection and repair of control parts and contacts. Figure 54 is a drawing showing the construction and assembly of a Kelman type 3D6A, 120,000-volt breaker. Figure 55 is a drawing of the contact and blade assembly, called the "pantograph," of a 70,000-volt Kelman breaker. The unique arrangement of

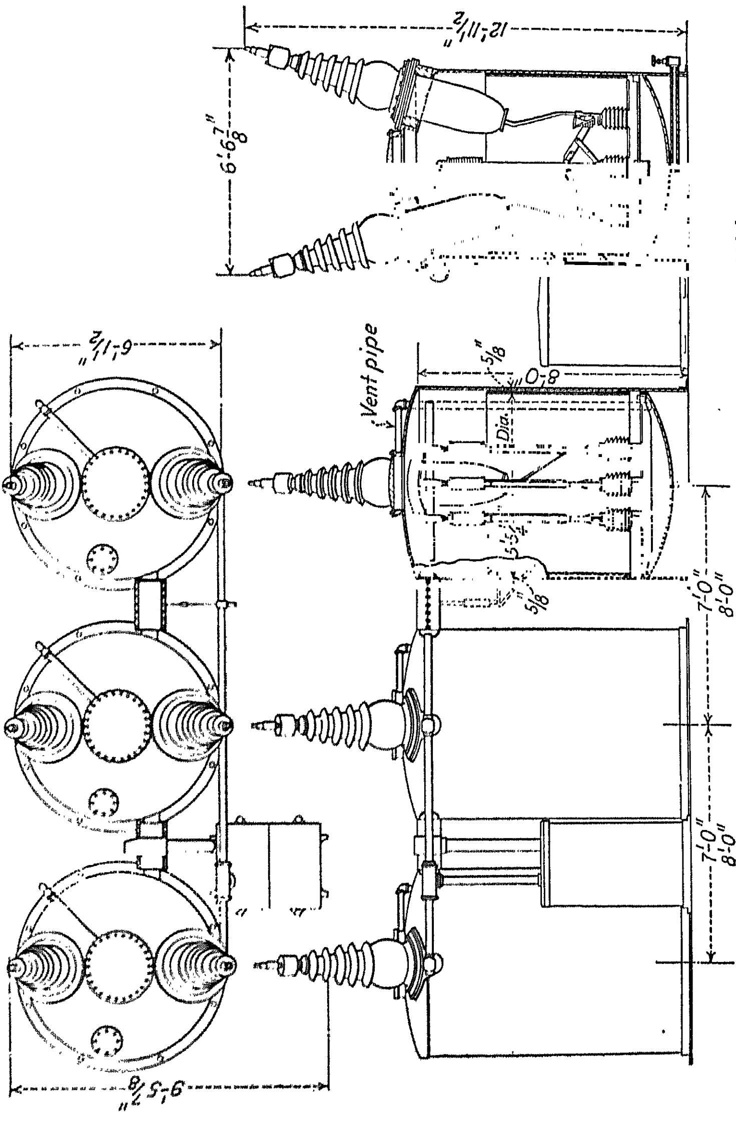


FIG. 54.—Kelman 3-D-6-A, 600-amp., 120-kv. oil circuit breaker, 500,000 kva.

contacts in the Kelman breakers is at once apparent from the two illustrations just referred to.

The Kelman line of circuit breakers is designated by certain type numbers, as follows:

Type	Breaker, volts
2D6A	70,000
5D6A	70,000
9D6A	70,000
3D6A	120,000
12D6A	132,000

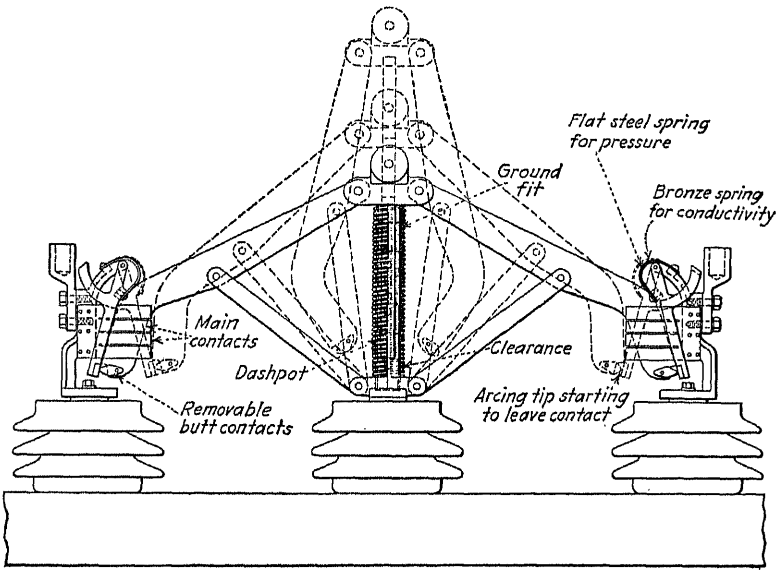


FIG. 55.—Kelman standard-type high-speed pantograph assembly.

In the same voltage class the higher numbers designate switches of greater interrupting capacity, while the numeral 6 identifies them as six-break oil switches. In Fig. 56 is shown the 2D6A motor-operated breaker; Fig. 57 shows the 9D6A solenoid-operated breaker; and Fig. 58 the 3D6A solenoid-operated breaker. Some four-break oil circuit breakers have been built of the same general design for lighter duty than six-break switches. A few ten-break breakers have been constructed, principally for installation

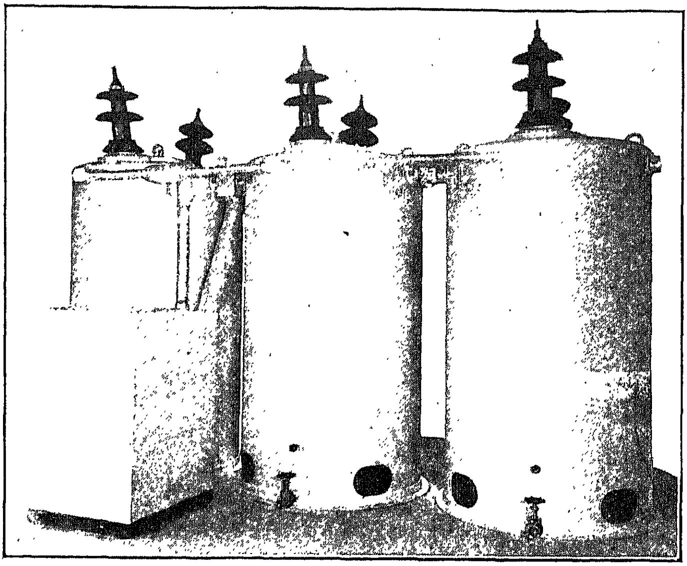


FIG. 56.—Kelman 2-D-6-A, 400-amp., 70-kv. motor-operated oil circuit breaker.

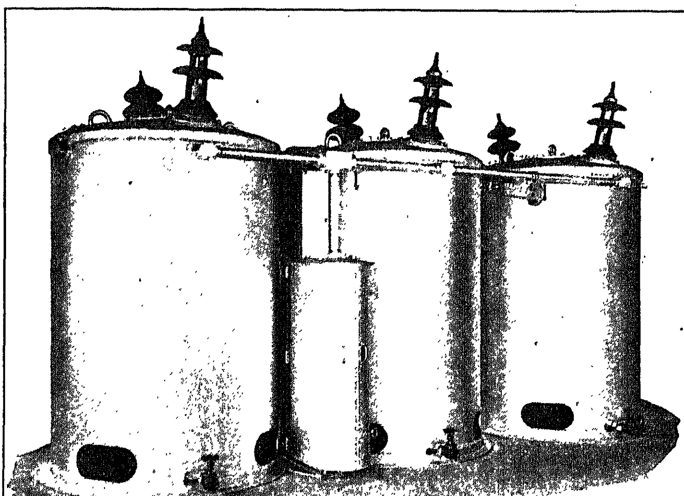


FIG. 57.—Kelman 9-D-6-A, 600-amp., 70-kv. solenoid-operated, oil circuit breaker.

and observation in actual service, but the standard line of breakers is of the six-break type. The main contacts are of the knife-blade and return-bend clip type. Butt-type arcing contacts are used as shown in Fig. 55. The moving blades have a pantograph motion that gives a double horizontal linear break. Three pantographs are placed in each tank and are operated by the crank arms on the operating

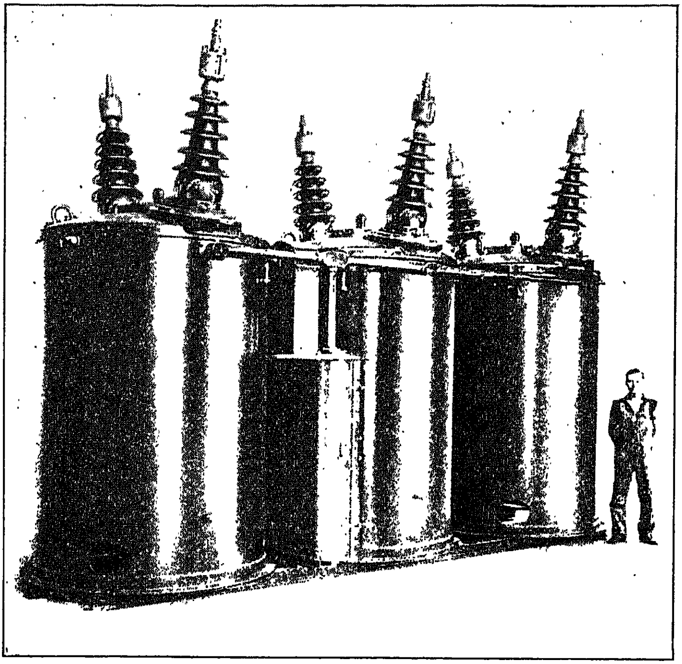


FIG. 58.—Kelman 3-D-6-A, 600-amp., 120-kv. solenoid-operated 1,000,000-kva. breaker.

shaft. The pantographs are cross-connected, thus giving six, practically simultaneous, breaks for each phase. The contacts are mounted on post-type insulator supports fastened to wooden boards set on edge, which are, in turn, bolted to the switch tanks. The insulating supports are arranged in the tank in such position as to give ample clearance on all sides. This construction relieves the entrance bushings from all mechanical strain due to the switch-operating parts.

In a letter to the authors, describing his breakers, Mr. Kelman says:

> We will begin to put in 10-break when we seem to have reached the safe limit [of interrupting capacity] on the 6-break, but before going to 10-break we aim materially to increase the head of oil above the contacts in the 6-break circuit breakers and to increase the thickness of the tanks.
>
> The depth, volume, and dead weight of oil above the contacts is very important, as in order to overcome the inertia of this large volume of oil, almost instantly, as the arcs try to do, tremendous pressure must be applied, and this pressure is on the arcs right at the time when it will do the most good and effectively breaks them. The large volume of oil rapidly cools gas bubbles and the breaker is ready for the next short.

In the foregoing statement may be found the explanation of another point in which the Kelman breakers differ from those of other manufacturers, namely, in the head or depth of oil above the contacts. In the Kelman 70,000-volt breakers, this depth is 5 ft. 3 in., as compared with 18 or 20 in. in other breakers. Two of the other manufacturing companies are, however, at the present time, increasing the head and volume of oil in their 120-kv. and higher-voltage breakers. One company, in particular, is building 120-kv. breakers at the present time with the same volume of oil in each tank and the same depth above the contacts as in Kelman breakers. This depth and volume are the same as were supplied in the original Kelman round-tank breakers first manufactured in 1921. There is a wide difference of opinion on the subject of depth of oil over the contacts, and the subject is still a matter of debate, with much to be said on each side.

In the earlier Kelman round-tank breakers, the tanks were all made from $\frac{1}{4}$-in. plate and no reinforcing was furnished around the bushings and manholes, so a manhole cover fastened with springs was furnished to relieve the pressure in the tanks after a short circuit. Several years of experience with a large number of these breakers have convinced the manufacturer that it was better practice to

reinforce the top of the tank so as to withstand, with a large factor of safety, the internal pressure and impact due to oil throw caused by the arc and to bolt down the manhole cover solidly, supplying only a small vent for gas escape. All Kelman breakers are now so constructed. This construction is clearly shown in Fig. 54. Closing up the breaker tank this way had no effect on the impact due to oil throw but did increase the pressure a small amount, due to confining the gas. Reinforcing the tops of the tanks, however, increased the resistance to withstand internal pressure more than seven times over that of the old design. As larger interrupting capacity is required, the tanks are made stronger so as to withstand the internal pressure with a large margin of safety. The additional cost of the heavier plate to obtain this great factor of safety only adds a small amount to the total cost of the breaker.

Tests have been made, jointly by the Kelman Company and a large operating company, to test the breaker tanks against internal gas pressure and oil impact. These tests have been made using blasting powder hung in bottles at the arcing-contact locations with oil in the tanks. The powder used was of a grade that would burn over a period of time approximately the same as the duration of the electric arc on short circuits as determined by oscillograph measurements. Measurement of impact, pressure, and tank jump were recorded by means of indicating instruments and pressure-card indicators, and a moving-picture record was kept of all tests. The design of the tank structure for modern-type Kelman circuit breakers, also head of oil and proportion of air volume to oil volume, has been based on the results of these tests.

The operating mechanism of the Kelman breaker consists of a shaft carried in babbited bearings in the top of each tank and provided with a crank arm outside the tank. Universal joints are furnished between the tanks. The three phases are operated by a rod connected to a lever on one of the universal joints, the bottom end of the rod

being fastened to the operating mechanism. Solenoid-, air-, or motor-wound-spring operating mechanisms are furnished. The solenoid mechanism is supplied with an auxiliary trip-free relay to prevent pumping of the breaker, while the motor and air mechanisms are mechanically trip free. As is the case with the Pacific Electric breakers, the Kelman breakers are not affected by the action of gravity and must have an operator for closing the breaker, and, also,

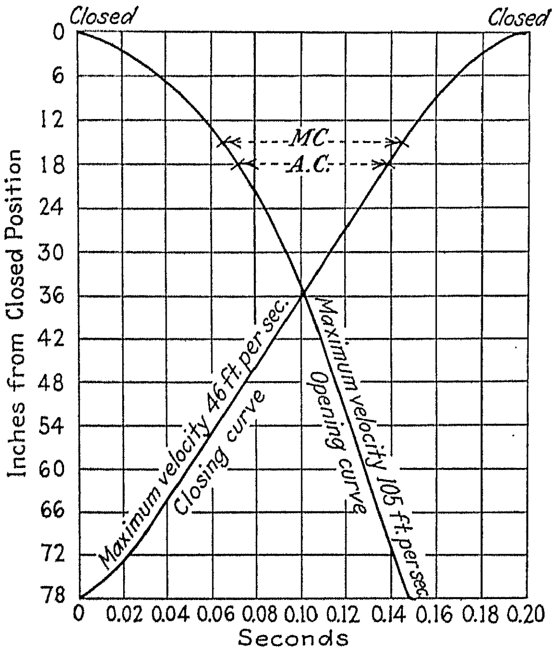


FIG. 59.—Kelman 3-D-6-A, 400-amp., 120-kv., KSM4-mechanism time curves.

means to open the breaker. In the Kelman breaker the means for opening the circuit breaker are the springs on the pantograph tube dashpots, as shown in Fig. 55. The dashpots, which are incorporated as a part of the pantograph assembly, give a quick check at the end of the opening stroke and prevent all rebound. The action of this dashpot is clearly shown in Fig. 59, showing velocity curves on a 3D6A breaker.

The solenoid supplied with the Kelman mechanism requires 160 amp. at 125 volts direct current to close a breaker and 20 amp. to open it. The motor mechanism requires the same amount of current to close the breaker as is required to open it. The solenoid mechanism requires a large storage battery and large control feeder cables to maintain a high operating voltage at the switch mechanism.

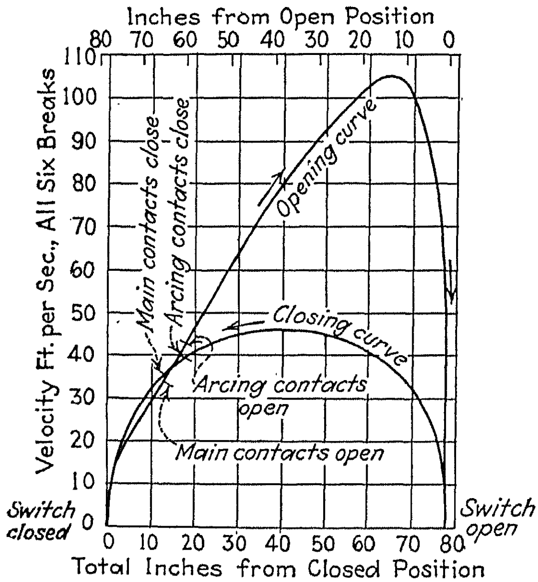


FIG. 60—Kelman 3-D-6-A, 400-amp., 120-kv. motor-mechanism velocity curves.

The solenoid is not so fast as a compressed spring unless it is so designed as to permit a very heavy current inrush.

The time and velocity curves for a Kelman type 3D6A, 120,000-volt motor-operated breaker are shown in Figs. 59 and 60. The velocity shown on the curves is for all six breaks, so the opening velocity for one break is 5.33 ft. per second at the point where arcing contacts part and 19.13 ft. per second at the point of maximum speed. The motor-operated breaker opens (complete time of mechanical travel) in 0.148 sec. and closes in 0.185 sec. (see Fig. 59),

whereas the same type breaker solenoid-operated requires 0.145 sec. to open and 0.355 sec. to close. The main advantage of the Kelman motor mechanism over the solenoid mechanism is in the low current required for operation and in the faster closing cycle. The advantage of the solenoid mechanism is its simplicity and resultant low cost as compared with the motor mechanism.

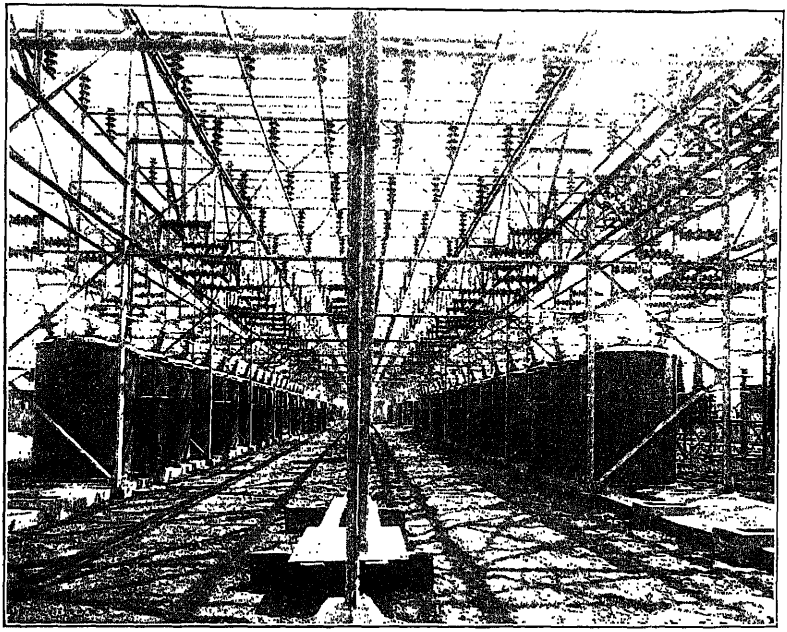


FIG. 61.—Fifty-four Kelman 9-D-6 and 9-D-6-A oil circuit breakers at Lightipe sub-station.

Kelman breakers have been extensively used by the Southern California Edison Company, the Bureau of Power and Light, Los Angeles, the Los Angeles Gas and Electric Company, San Joaquin Light and Power Corporation, the Southern Sierras Power Company, and a number of other companies. Figure 61 is a photograph of the 70-kv. bus structure at Lightpipe substation, with 54 Kelman 9D6 and 9D6A breakers in service. The energy available on short circuit at this station is on the order of 1,500,000 kva.

The Edison Company has also purchased Kelman 70-kv. breakers of the 9D6A type for their new La Fresa substation. With several years of operation to justify these installations, and with no major breaker failures recorded, it would appear that the Kelman design is such as will successfully interrupt heavy short circuit.

Due to the fact that Kelman breakers have been used almost exclusively on the Pacific Coast, no attempt having been made to market them in the Middle West or Far East, very few records were kept in the past of the actual short-circuit conditions to which the breakers have been subjected. During the past few years, however, many records have been obtained of short-circuit duty on Kelman breakers installed on two of the larger Southern California systems, and actual short-circuit tests have been made on some of the smaller breakers. Oscillographs are, at present, connected to the busses of some of the above companies' larger substations where Kelman breakers are installed, and much valuable information has been obtained from the records and tests thus obtained by the operating companies.

CHAPTER XIII

CONDIT HIGH-VOLTAGE OIL CIRCUIT BREAKERS

THE Condit Electrical Manufacturing Corporation of Boston, Mass., manufactures a line of high-voltage oil circuit breakers under the type designation "FO–40," for potentials ranging from 25 to 88 kv. The Condit Electrical Manufacturing Corporation became associated with the American Brown Boveri Electric Corporation in 1925, and at that time a new line of breakers known as the "type BO–60" for potentials from 110 to 220 kv. was added to the line. All breakers are marketed through Condit, and as the two types are radically different in design they will be considered separately.

The type FO–40 breakers are frame mounted and of unusually strong construction throughout.

They are furnished for 4,000 amp. or less, 25 kv.; 2,000 amp. or less, 37 kv.; and 1,200 amp. or less for 50, 73, and 88 kv., classified in six sizes, X, A, B, C, D, and F, in accordance with interrupting rating.

The suffix letters X, A, B, etc., stand for the following interrupting-capacity ratings:

X = 125,000 kva.[1]	A = 350,000 kva.	B = 500,000 kva.
C = 750,000 kva.	D = 1,000,000 kva.	F = 1,500,000 kva.

[1] At 73,000 volts, X = 150,000 kva.; and at 88,000 volts, X = 250,000 kva.

Construction.

The tanks are cylindrical in shape, with bumped bottoms. Sides and bottom are of thick steel plate strongly welded at joints. The tank sides vary in thickness from $\frac{3}{16}$ to $\frac{1}{2}$ in. and the bottom from $\frac{5}{16}$ to $\frac{5}{8}$ in., in accordance with interrupting ratings.

The tanks have the so-called "short-tank" bolt suspension throughout, which reduces elongation under excessive strains to a minimum and prevents escape of oil.

On the low interrupting-capacity sizes, the tank bolts extend from the frame to lugs welded to the tank sides; on the large-capacity sizes, the bolts extend to a circular steel ring doubly welded to the tank side.

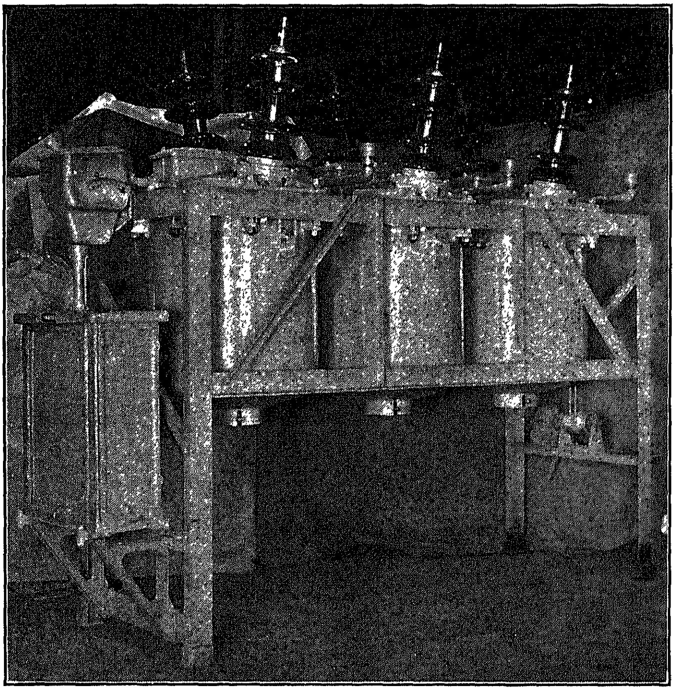


FIG. 62.—Condit FO-40-73B, 73-kv. frame-mounted oil circuit breaker.

Each tank unit is arranged for gaskets and equipped with oil-drain valve, oil sampling valve, and oil gage suitably located. A high dielectric tank lining approximately $\frac{1}{4}$ in. thick is provided as an additional safeguard to prevent an abnormal arc carrying to the tank wall.

The top castings are of steel and have provision for mounting the bushings, pole-unit mechanisms, bushing

transformers, vents, and tank bolts which clamp the tank to the top casting.

Top castings vary from $\frac{5}{8}$ to $\frac{3}{4}$ in. in thickness and are reinforced with webs on the under side of the casting formed by the mechanism and bushing-transformer compartments. Holes are placed in the mechanism well, so that balanced pressures are maintained in all parts of the structure above the oil level.

To each pole unit is coupled a 2-in. pipe, which carries the oil and gas separator of the centrifugal type, which by

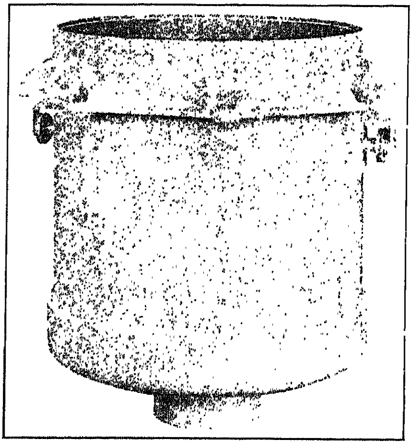


FIG. 63.—Condit FO-40 tank.

using centrifugal force serves to force the oil out of the gas stream, thus effectively preventing the blowout of large quantities of oil and still effecting an efficient release for the gas pressure. A valve automatically resets after the relief has been obtained and seals the breaker from intake of moisture. Another important feature is that the connecting rods between pole units are provided with sliding gaskets so as to prevent gases generated in one pole unit from escaping around these rods.

The X breaker has two breaks in series; A, B, C, and D, four breaks; and F-size breaker, six breaks in series. The

arcing contacts are so designed as effectively to prevent the burning of the inside sliding members, thus preventing the slowing up or decrease in opening speed due to burned-out or pitted auxiliary contact members.

The contact arrangement of the four-break arrangement is shown in Fig. 64. The main current-carrying contacts shown by the number 22 are of laminated copper and make

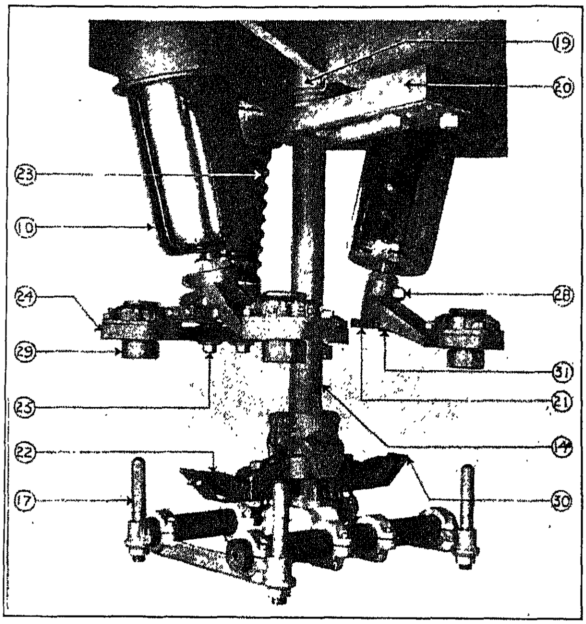


Fig. 64.—Contacts, type FO-40 oil circuit breaker.

a wiping contact against the flat contact surface 21. The main contacts are protected against the possibility of arcing and burning by a set of secondary arcing type 30, which part after the main contacts have separated and before the final break is made by the rod-and-segment contacts 17 and 29. The location of these final-break contacts is favorable for good breaker operation. They are well away from the main contacts and sufficiently separated from one another to keep the arcs and gas bubbles from combining.

The arcs are broken under oil which has the least possible agitation due to the movement of circuit-breaker parts during the opening process, and the tendency of the arc is to blow away from all contact parts and out into the oil.

All type FO-40 breakers are furnished with either direct-current solenoid or alternating- or direct-current motor-operated mechanism. These operating mechanisms are of

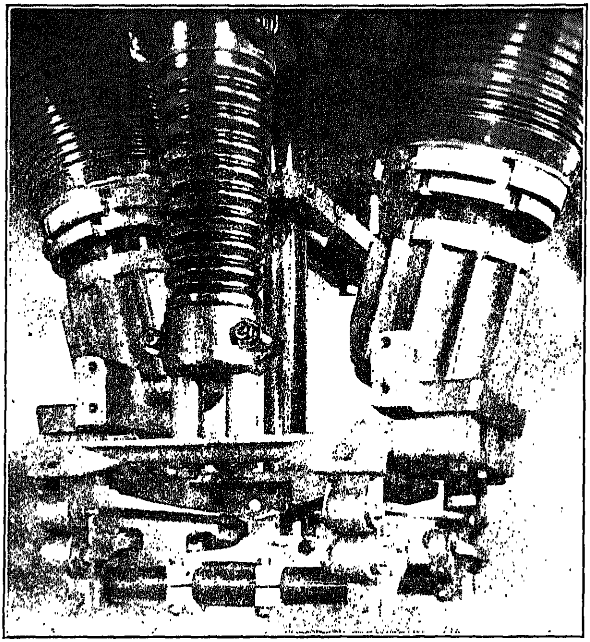


Fig. 65.—Type FO-40-25D, 4,000-amp. contacts for 25,000 volts.

ample capacity to handle the breaker properly under the most adverse conditions.

Mechanical trip free action is furnished on all hand- and motor-operated breakers and may, also, be supplied on solenoid-operated types.

In regard to the speed of the breaker, the operating mechanism is a simple toggle linkage of light weight inherently fast when the toggle collapses on the opening stroke

(see Figs. 66 and 67). Powerful springs impart high rate of acceleration to the moving member, and the design is such that the maximum speed of the contacts is practically obtained at a point where the arcing contacts separate.

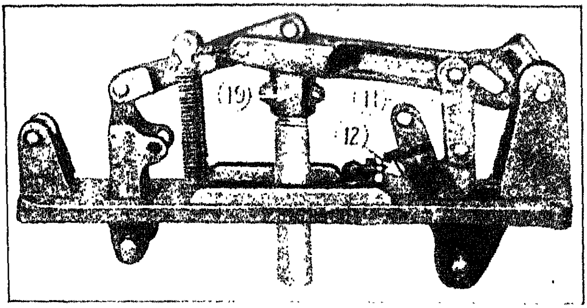


FIG. 66.—Condit linkage.

The actual mechanical speed of the contact members is not necessarily a criterion of the high-speed characteristics as generally implied to the breaker, meaning the time duration of arc interruption.

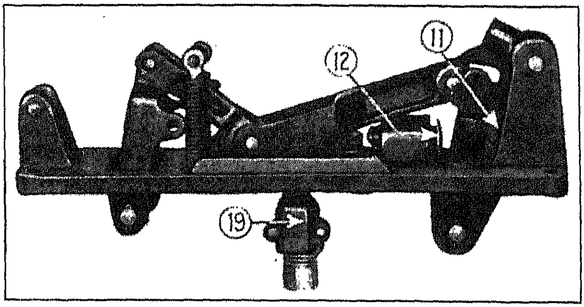


FIG. 67.—Condit linkage.

It should, also, be borne in mind that the four-break breaker moving at a rate of 5 ft. per second is increasing its effective arc length at the rate of 20 ft. per second.

The type FO–40 breakers are furnished with all-porcelain dry-type bushings of the Ohio Insulator Company's or

equivalent manufacturer's make, except the 73,000-volt, F size and the 88,000-volt, D size, which are furnished with oil-filled bushings.

The type BO-60 breakers have many of the characteristics of the European breakers and have an entirely different appearance from the usual American ones. The design follows very closely the design of the Brown Boveri breakers built in Baden, Switzerland, but with modifications to meet American practice. A typical BO-60 breaker is shown in Fig. 68, which represents a 154-kv. breaker with a rated rupturing capacity of 1,500,000 kva.

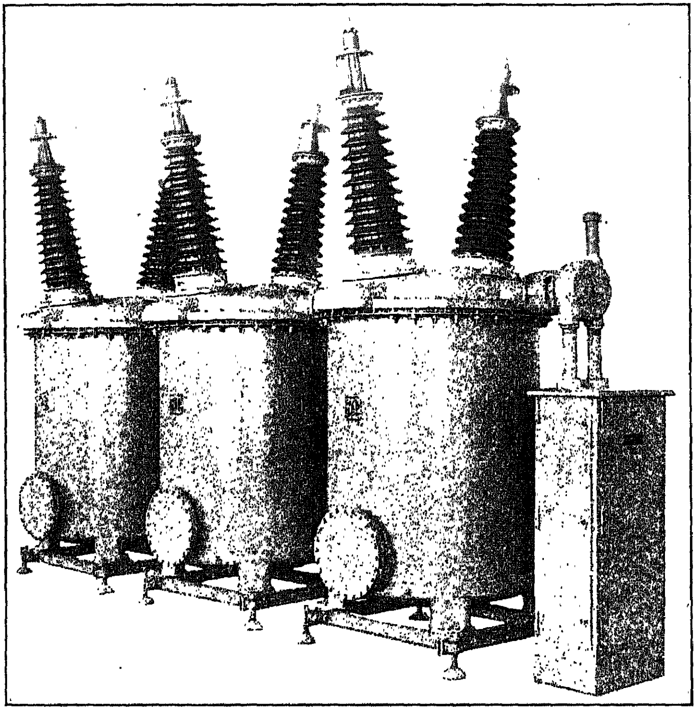


FIG. 68.—Type BO-60, 154-kv. American Brown Boveri oil circuit breaker.

All BO-60 breakers are of the circular-tank type, with rounded or bumped bottoms welded to the tank wall by

means of a lap weld on both the inside and the outside. Tops are of cast steel. The design of the top is such as to eliminate all covers and manholes, thus giving a top with an unbroken surface except for the entrance holes for the bushings. Extra-heavy flanges in the shape of a ring around the top of the tank form the seat to which the top casting is fastened by a large number of 1-in. bolts placed at small, regular intervals.

The manhole is located at the side of the breaker near the bottom of the tank, which permits repairs or adjustments without the necessity of going through the top of the breaker. The location of the manhole in high-tension breakers has considerable weight in determining the diameter of the tank; if it is placed on the side, a smaller tank diameter may be used. If the manhole is placed in the top, even though a larger tank diameter is used, the mechanism must be so designed as to allow a man to get through the manhole and down into the tank.

The general arrangement of parts is that each bushing on its lower end supports a series of stationary contacts. Secured to the top, or cover, are two heavy wooden rods, which form a guide for the moving element to insure up and down travel in a true vertical plane. The operating shaft extends directly through the pole units, and a rotary motion is imparted to the shaft to close the breaker. At two points on this operating shaft, cranks are fixed. Each crank connects with a lifting rod, thus using two lifting rods to suspend the moving element. The breaker is opened or closed with approximately one-half turn on the operating shaft.

The breaker travel on the opening stroke is limited by means of a bumper attached to the shaft, the bumper striking on a seat attached to the top or frame. Definite limitation of travel is, thus, assured. There is a powerful tortional-type accelerating spring wound around the operating shaft. On closing the breaker, this spring is cocked so as to exert its ability when the latch is tripped and the moving element

starts downward. The type of rotary mechanism used allows the maximum use of the space between bushings. As a consequence, the bushings can be placed fairly close together and, at such an angle, will allow maximum clearances under oil and maximum clearance between live parts at their terminals in air.

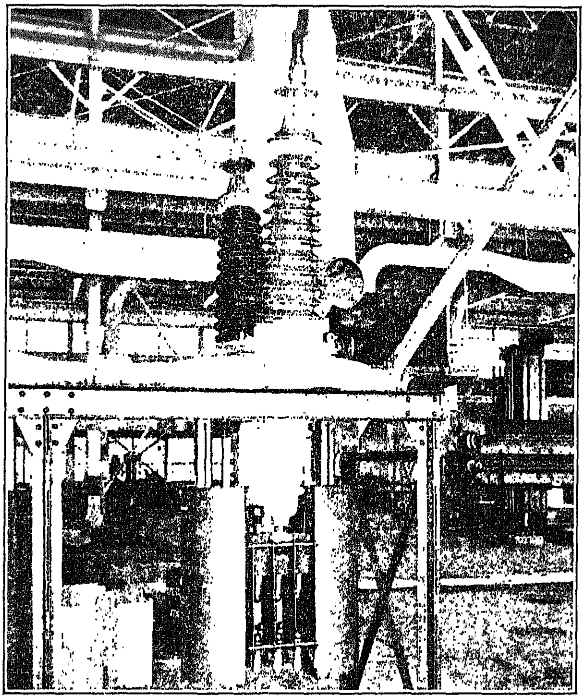


FIG. 69.—Type BO-60, 154-kv. details.

Bushings are of the oil-filled type using single porcelain shells for the upper and lower sections.

The type BO-60 high-tension oil circuit breakers are of the multibreak type with ten breaks per pole. The contact arrangement is shown in Fig. 69. The general mechanical arrangement is very simple. Each bushing supports one set of the stationary contacts, and the moving element supports an equal number of contacts. Barriers of high

dielectric material are placed between arcing contacts and so arranged that they may be swung out of the way when it is desired to work on the contacts or make adjustments. The contacts themselves are spherical in shape and make a butt contact.

Considerable advantage is claimed for the spherical contacts as having a high thermal absorption ability with low volatilization of copper. It is also claimed that the arrangement of break is such as to secure the maximum effect of the magnetic blowout and yet so to direct the arc as to obtain maximum clearances.

In regard to the speed of the breaker, the powerful tortional accelerating spring, assisted by gravity, imparts a high rate of acceleration to the moving member, and this, in turn, is multiplied by the multiple breaks of ten or more in series, affording an extremely high effective speed of circuit interruption.

As was the case with the type FO–40, the operating mechanism supplied with the type BO–60 is a strong feature of the breaker. This mechanism is of the direct motor-operated type and has ample capacity to handle the breaker properly under the heaviest conditions. The entire design of the operating mechanism is distinctly European and is especially designed to handle the multiple-break system. The mechanism speed, while not so fast as may be obtained on two-break breakers, is relatively fast, and when mechanical speed is multiplied by the number of breaks in series, the effective speed of interruption is extremely high.

The 110-kv. BO–60 circuit breaker has 11 in. of travel of contacts from full-open to full-closed position, but the ten breaks in series give an effective separation of 110 in., which is many times greater than can be obtained in a two-break breaker with economy.

It is interesting to note that on a type BO–60 interrupting-capacity test made by a southern public utility at 500,000 kva., the time for one OCO (throwing short on line to removal of same) was 16 cycles, including relay time.

RATINGS[1]

Type	Rated volts	Rated current	Interrupting-capacity rated voltage	
			Amp.	Kva.
FO-40-73X	73,000	600, 800	1,200	150,000
B	73,000	600, 1,200	4,000	500,000
D	73,000	600, 1,200	8,000	1,000,000
F	73,000	600, 1,200	12,000	1,500,000
FO-40-88X	88,000	600, 800	1,650	250,000
D	88,000	600, 1,200	6,500	1,000,000
BO-60-110B	110,000	400, 600	5,250	1,000,000
132E	132,000	400, 600	5,480	1,250,000
154G	154,000	400, 600	5,650	1,500,000
187H	187,000	400, 600	5,400	1,750,000
220K	220,000	400, 600	5,250	2,500,000
220L	220,000	.....	......	4,000,000
380L	380,000	.....	......	4,000,000

[1] See N. E. L. A. rules on page 110.

73,000-VOLT OIL CIRCUIT BREAKERS FOR RUPTURING CAPACITIES BELOW 1,000,000 KVA.

Manufacturer	Westinghouse	General Electric	Condit	Pacific Electric	Westinghouse	General Electric	Kelman	Condit	Pacific Electric
Type	G-10	FKO-136-2046A-F73A	FO-40-73X	JB-45	G-22-5	FKO-139-42A-F73A	2D6A	FO-40-73B	R-45
Rating:									
Voltage	73,000	73,000	73,000	73,000	73,000	73,000	73,000	73,000	73,000
Continuous current	400 600	400 800	600 1,200	400 600	600 1,200	600 1,200	400	600 1,200	400 600
Five-second capacity	20,000 30,000	20,000 40,000	....	20,000 30,000	30,000	30,000 40,000	16,000	....	20,000 30,000
Rupturing capacity, amp.	1,200	1,200	1,200	2,600	4,000	4,000	4,000	4,000	6,150
Rupturing capacity, kva.	150,000	150,000	150,000	330,000	500,000	500,000	500,000	500,000	750,000
Physical characteristics:									
Service	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor
Overall length	140 in.	174$\frac{3}{4}$ in.	....	205$\frac{5}{8}$ in.	177 in.	201$\frac{3}{4}$ in.	183$\frac{1}{2}$ in.	175 in.	226$\frac{3}{8}$ in.
Overall width	50 in.	64$\frac{1}{8}$ in.	....	82$\frac{1}{4}$ in.	56 in.	64 in.	75$\frac{1}{2}$ in.	56 in.	82$\frac{1}{4}$ in.
Overall height	161 in.	164$\frac{1}{2}$ in.	....	138 in.	175 in.	173$\frac{5}{8}$ in.	123 in.	132 in.	138 in.
Height to top of tank	113$\frac{3}{8}$ in.	113 in.	....	....	123 in.	116 in.	100 in.	99 in.	
Spacing between phases	40 in.	52 in.	....	54$\frac{1}{8}$ in.	45 in.	52 in.	62 in.	45 in.	54$\frac{1}{8}$ in.
Spacing between terminals	37 in.	59 in.	....	41$\frac{1}{4}$ in.	....	58 in.	49 in.	39$\frac{5}{8}$ in.	41$\frac{1}{4}$ in.
Minimum ground clearance	....	....	....	....	....	....	23 in.		
Weight without oil	6,600	9,740	....	....	11,500	11,900	9,000	....	10,400
Weight of complete breaker	8,850	13,700	16,500	....	17,000	19,300	24,750	17,990	17,800
Tank:									
Shape	Elliptical	Oval	Round	Round	Round	Round	Round	Round	Round
Type of bottom	Flat	Flat	Convex	Convex	Convex	Convex	Convex	Convex	Convex
Material	Welded steel	Welded steel	Welded steel	$\frac{3}{16}$ in. welded steel	Welded steel	Welded steel	$\frac{1}{4}$ in. boiler plate	Welded steel	$\frac{5}{16}$ in. welded steel
Material of top	Cast steel	Cast iron	Cast steel	Cast steel	Welded steel	Welded steel	$\frac{1}{4}$ in. boiler plate	Cast steel	Cast steel
Tank diameter	22 by 34 in.	20 by 46 in.	34 in.	45$\frac{3}{4}$ in.	36 in.	42 in.	54 in.	33 in.	45$\frac{1}{2}$ in.
Tank depth	43$\frac{3}{8}$ in.	57 in.	....	33$\frac{1}{2}$ in.	69$\frac{1}{4}$ in.	55$\frac{3}{8}$ in.	96 in.	....	44$\frac{5}{8}$ in.
Gallons of oil per pole	100	174	....	200	242	280	750	....	266
Height of oil over contacts	....	....	....	19$\frac{1}{2}$ in.	....	....	63	....	19$\frac{1}{5}$ in.
Location of manhole	None	None	....	None	None	None	In top	None	None
Size of manhole	....	....	....	....	....	....	20 in.		
Is tank liner used?	Yes	Yes	....	Yes	Yes	Yes	Yes	....	Yes

Type	Condenser	[illegible]	[illegible]	No. 29,595			No. 28,104		
Dry flashover	225 kv.	240 kv.	....	205 kv.	225 kv.	240 kv.	175 kv.	....	205 kv. 220 kv.
Wet flashover	190 kv.	200 kv.	....	165 kv.	190 kv.	200 kv.	135 kv.	....	165 kv. 180 kv.
Main contacts:									
Type	Butt	Wedge and finger	Laminated brush	Blade and jaw	Wedge and finger	Wedge and finger	Blade and jaw	Laminated brush	Blade and jaw
Action	Plain break	Plain break	Plain break	Horiz. rotating	Plain break	Plain break	Horiz. linear	Plain break	Horiz. rotating
Number per pole	2	2	2	2	2	2	6	2	6
Contact travel	16 in.	....	....	17½ in.	21 in.	....	10¼ in.	....	17½ in.
Total break	30 in.	36 in.	....	21¼ in.	35 in.	36 in.	47 in.	....	65¼ in.
Clearance to tank	....	....	....	7¾ in.	....	....	5½ in.	....	7⅝ in.
Distance between contacts	....	....	....	4 by 24 in.	....	....	12 in.	....	4 by 24 in.
Secondary contacts:									
Type	Butt	None	Rod and segment	Sliding blade	Wedge and finger	None	Swinging butt	Rod and segment	Sliding blade
Action	Plain break	....	Plain break	Plain break	Quick break	....	Plain break	Plain break	Main break
Number per pole	2	....	4	2	2	....	6	4	6
Operator:									
Type	Solenoid *	Motor	....	Motor-wound springs ¶	Solenoid ‡	Motor	Motor or solenoid	....	Motor-wound springs ¶
Closing current	45 amp.	90–115	....	2.66	150 amp.	90–115	20 175	....	5.7
Tripping current	4.6 amp.	3	....	2.66	5 amp.	3	20 20	....	5.7
Operating voltage	125 d. c.	125 d. c. †	....	125 d. c.	125 d. c.	125 d. c. §	110 125	....	125 d. c.
Inch-pounds force	....	....	....	3,000	....	....	18,000 13,920	....	12,000
Is operator trip free?	Yes	Yes	....	Yes	Yes	Yes	Yes Yes ‖	....	Yes
Operating characteristics:									
Dead time									
Opening time, no voltage									
Opening time, rated amp.									
Closing time									
Contact rebound, inches									

* Motor available. † Motors can be supplied for 250-v. d.c. and 220-v. 60-cycle a.c. ‡ Motor available. § Motors can be supplied for 250-v. d.c. and 220-v. 60-cycle a.c.
‖ Solenoid mechanism requires a special "trip-free relay." ¶ Motor 110–220 a.c., 125–250 or 24 d c.

73,000-VOLT OIL CIRCUIT BREAKERS FOR RUPTURING CAPACITIES OF 1,000,000 KVA. AND ABOVE

Manufacturer	Westinghouse	General Electric	Kelman	Condit	Kelman	Pacific Electric	General Electric	Kelman	Condit
Type	G-222-S	FHKO-139-42B-F73A	2D6A	FO-40-73D	5D6A	RW-52 Floor mounted	FHKO-139-48C-F73A	9D6A	FO-40-73F
Rating:									
Voltage	73,000	73,000	73,000	73,000	73,000	73,000	73,000	73,000	73,000
Continuous current	600 1,200	600 1,200	400	600 1,200	400	600	600 1,200	600	600 1,200
Five-second capacity	30,000	30,000 40,000	16,000	12,000	16,000	30,000	30,000 40,000	23,000	
Rupturing capacity, amp.	8,000	8,000	8,000	8,000	10,000	12,000	12,000	12,000	12,000
Rupturing capacity, kva.	1,000,000	1,000,000	1,000,000	1,000,000	1,250,000	1,500,000	1,500,000	1,500,000	1,500,000
Physical characteristics:									
Service	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor
Overall length	194 in.	$201\frac{3}{4}$ in.	$183\frac{1}{2}$ in.	175 in.	$183\frac{1}{2}$ in.	$275\frac{1}{4}$ in.	$222\frac{3}{8}$ in.	226 in.	$224\frac{3}{4}$ in.
Overall width	63 in.	64 in.	$75\frac{1}{2}$ in.	56 in.	$75\frac{1}{2}$ in.	$72\frac{7}{8}$ in.	$71\frac{3}{4}$ in.	$83\frac{3}{4}$ in.	$69\frac{1}{2}$ in.
Overall height	182 in.	$197\frac{3}{8}$ in.	123 in.	132 in.	123 in.	$166\frac{3}{4}$ in.	$213\frac{1}{4}$ in.	$128\frac{1}{2}$ in.	$173\frac{5}{8}$ in.
Height to top of tank	130 in.	140 in.	100 in.	99 in.	100 in.	110 in.	155 in.	102 in.	117 in.
Spacing between phases	50 in.	52 in.	62 in.	45 in.	62 in.	84 in.	59 in.	76 in.	57 in.
Spacing between terminals	$42\frac{1}{2}$ in.	58 in.	49 in.	$39\frac{5}{8}$ in.	49 in.	76 in.	$61\frac{3}{4}$ in.	63 in.	$58\frac{5}{8}$ in.
Minimum ground clearance	...	...	...	...	23 in.	$41\frac{1}{4}$ in.			
Weight without oil	15,700	12,430	14,000	...	18,500	14,000	17,900	22,000	
Weight of complete breaker	22,850	21,800	29,750	18,300	34,250	30,000	30,700	45,800	28,300
Tank:									
Shape	Round	Round	Round	Round	Round	Round	Round	Round	Round
Type of bottom	Convex	Convex	Convex	Convex	Convex	Convex	Convex	Convex	Convex
Material	Welded steel	Welded steel	$\frac{1}{2}$-in. boiler plate	Welded steel	$\frac{5}{8}$-in. boiler plate	$\frac{3}{8}$-in. welded steel	Welded steel	$\frac{5}{8}$-in. boiler plate	Welded steel
Material of top	Welded steel	Welded steel	$\frac{1}{2}$-in. boiler plate	Cast steel	$\frac{5}{8}$-in. boiler plate	$\frac{3}{8}$-in. welded steel	Welded steel	$\frac{5}{8}$-in. boiler plate	Cast steel
Tank diameter	42 in.	42 in.	54 in.	38 in.	54 in.	52 in.	48 in.	66 in.	48 in.
Tank depth	75 in.	$67\frac{3}{8}$ in.	96 in.	...	96 in.	93 in.	75 in.	96 in.	
Gallons of oil per pole	317	345	750	...	750	700	520	1,133	380
Height of oil over contacts	...	...	63	...	57	40	...	57	
Location of manhole	None	None	In top	...	In top	Side of tank	None	In top	None
Size of manhole	...	...	20 in.	...	20 in.	20 in.	...	24 in.	
Is tank liner used?	Yes	Yes	Yes	...	Yes	Yes	Yes	Yes	
Bushing:									
Make	Westinghouse	General Electric	Ohio Brass	Ohio Brass	Ohio Brass	Ohio Brass or Locke	General Electric	Ohio Brass	Ohio Brass

Type	Condenser	Oil filled	Solid, Cat. No. 28,104	Oil filled	Solid, Cat. No. 29,283	Solid Solid	Oil filled	Solid, Cat. No. 29,283	Oil filled
Dry flashover	225 kv.	240 kv.	175 kv.	...	175 kv.	205 kv. 220 kv.	240 kv.	175 kv.	
Wet flashover	190 kv.	200 kv.	135 kv.	...	135 kv.	165 kv. 180 kv.	200 kv.	135 kv.	
Main contacts:									
Type	Wedge and finger	Wedge and finger †	Blade and jaw	Laminated brush	Blade and jaw	Blade and jaw	Wedge and finger ○	Blade and jaw	Laminated brush
Action	Plain break	Plain break	Horiz. linear	Plain break	Horiz. linear	Horiz. rotating	Plain break	Horiz. linear	Plain break
Number per pole	2	2	6	2	6	6	2	6	2
Contact travel	24½ in.	...	10¼ in.	...	10¼ in.	13½ in.	...	13 in.	
Total break	42 in.	32 in.	47 in.	...	47 in.	81 in.	40 in.	63 in.	
Clearance to tank	...	...	5¼ in.	...	5⅓ in.	7½ in.	...	7½ in.	
Distance between contacts	...	...	12 in.	...	12 in.	25 in.	...	15 in.	
Secondary contacts:									
Type	Wedge and finger	Rod and segment	Swinging butt	Rod and segment	Swinging butt	Sliding blade	Rod and segment	Swinging butt	Cylindrical butt
Action	Quick break	Explosion chamber	Plain break	Plain break	Plain break	Plain break	Explosion chamber	Plain break	Plain break
Number per pole	2	2	6	4	6	6	2	6	6
Operator:									
Type	Solenoid *	Motor	Motor or solenoid	...	Motor or solenoid	Motor-wound springs ¶	Motor	Motor or solenoid	
Closing current	150	90–115	20 175	...	20 180	5	90–115	20 175	
Tripping current	5	3	20 20	...	20 27	5	3	20 22.5	
Operating voltage	125 d.c.	125 d.c. ‡	110 125	...	110 125	125 d.c.	125 d.c. □	110 125	
Inch-pounds force	...	...	18,000 13,920	...	18,000 13,920	12,000	...	30,000 28,500	
Is operator trip free?	Yes	Yes	Yes Yes §	...	Yes Yes ‖	Yes	Yes	Yes Yes ⊙	
Operating characteristics:									
Dead time									
Opening time, no voltage									
Opening time, rated amp.									
Closing time									
Contact rebound, inches									

* Motor available. † For 1,200 amp. only. Rod and segment below 1,200 amp. ‡ Also, 250 d.c. and 220 a.c. § Solenoid mechanism requires a special "trip-free relay." ‖ Solenoid mechanism requires a special "trip-free relay." ¶ Motor 110–220 a.c., 125–250 or 24 d.c. ⊙ Solenoid mechanism requires a special "trip-free relay." □ Motor can be supplied for 250 volts d. c. and 220 volts, 60 cycle a. c.

110,000-Volt Oil Circuit Breakers for Rupturing Capacities Below 1,000,000 Kva.

Manufacturer	General Electric	Westinghouse	General Electric	Pacific Electric	Kelman
Type	FKO-136-3258A-F2	G-111	FKO-139-54-F2	RW-52	3D6A
Rating:					
Voltage	110,000	110,000	110,000	115,000	110,000
Continuous current	800	600	600	600	600
Five-second capacity	40,000	30,000	30,000	30,000	23,000
Rupturing capacity, amp.	1,300	2,600	2,600	2,600	2,600
Rupturing capacity, kva.	250,000	500,000	500,000	500,000	500,000
Physical characteristics:					
Service	Outdocr	Outdocr	Outdoor	Outdocr	Outdoor
Overall length	$238\frac{1}{4}$ in.	200 in.	$280\frac{1}{2}$ in.	$275\frac{1}{4}$ in.	226 in.
Overall width	$83\frac{1}{2}$ in.	83 in.	$77\frac{1}{8}$ in.	$72\frac{7}{8}$ in.	$83\frac{3}{4}$ in
Overall height	138 in.	185 in.	$162\frac{1}{2}$ in.	$166\frac{3}{4}$ in.	$156\frac{3}{4}$ in.
Height to top of tank	66 in.	99 in.	92 in.	110 in.	106 in.
Spacing between phases	72 in.	68 in.	84 in.	84 in.	76 in.
Spacing between terminals	78 in.	68 in.	$69\frac{1}{8}$ in.	76 in.	64 in.
Minimum ground clearance	.....	.....	.....	$36\frac{1}{2}$ in.	$35\frac{1}{2}$ in.
Weight without oil	14,880	17,500	20,675	14,000	17,000
Weight of complete breaker	24,000	35,000	33,950	30,000	40,800
Tank:					
Shape	Oval	Elliptical	Round	Round	Round
Type of bottom	Flat	Convex	Convex	Convex	Convex
Material	Welded steel	Welded steel	Welded steel	$\frac{3}{8}$-in. welded steel	$\frac{1}{4}$-in. boiler plate
Material of top	Cast iron	Welded steel	Welded steel	$\frac{3}{8}$-in. welded steel	$\frac{1}{4}$-in. boiler plate
Tank diameter	32 by 58 in.	58 in.	54 in.	52 in.	66 in.
Tank depth	66 in.	84 in.	72 in.	93 in.	96 in.
Gallons of oil per pole	400	780	590	700	1133
Height of oil over contacts	.....	.....	.....	40	$53\frac{3}{4}$
Location of manhole	Top casting	In top	Side of tank	Side of tank	In top
Size of manhole	.....	.....	17 in.	20 in.	18 by 21 in.
Is tank liner used?	Yes	No	Yes	Yes	Yes

Bushing:					
Make	General Electric	Westinghouse	General Electric	Ohio Brass or Locke	Ohio Brass
Type	Oil filled	Condenser	Oil filled	Oil filled	Oil filled, 27,382
Dry flashover	320 kv.	375 kv.	320 kv.	325	325
Wet flashover	250 kv.	330 kv.	250 kv.	256	220
Main contacts:					
Type	Wedge and finger	Butt	Wedge and finger	Blade and jaw	Blade and jaw
Action	Plain break	Plain break	Plain break	Plain break	Horiz. linear
Number per pole	2	2	2	6	6
Contact travel	....	$27\frac{1}{2}$	....	$12\frac{3}{8}$	13
Total break	36	50	54	$49\frac{7}{8}$	63
Clearance to tank	....	....	....	$11\frac{1}{2}$	$7\frac{3}{4}$
Distance between contacts	....	....	....	$18\frac{3}{4}$	15
Secondary contacts:					
Type	None	Butt	None	Sliding blade	Swinging butt
Action	....	Plain break	....	Plain break	Plain break
Number per pole	....	2	....	6	6
Operator:					
Type	Motor	Solenoid †	Motor	Motor-wound spring ‡	Motor or solenoid
Closing current	90–115	150	90–115	125 volt 5 24 volt 7	20 160
Tripping current	3	5	3	125 volt 5 24 volt 7	20 23
Operating voltage	125 d.c.*	125 d.c.	125 d.c.*	125 d.c. 24 d.c.	110 125
Inch-pounds force	....	....	....	20,000	30,000 28,500
Is operator trip free?	Yes	Yes	Yes	Yes	Yes Yes §
Operating characteristics:					
Dead time					
Opening time, no voltage					
Opening time, rated amp.					
Closing time					
Contact rebound, inches					

* Motors can be supplied for 220-v., 60-cycle a.c. and 250-v. d.c. † Motor available. ‡ Motors 110–220 a.c., 125–250 or 24 d.c. § Solenoid mechanism requires a special "trip-free relay."

110,000-VOLT OIL CIRCUIT BREAKERS FOR RUPTURING CAPACITIES OF 1,000,000 KVA. AND ABOVE

Manufacturer	Westinghouse	General Electric	Pacific Electric	Kelman	Condit Brown Boveri	Westinghouse	General Electric	Pacific Electric
Type	G-22-S	FHKO-139-54B-F2	RW-58	3D6A	BO-60-115	G-222-5	FHKO-139-60C-F2	RW-64
Rating:								
Voltage	110,000	110,000	115,000	110,000	115,000	110,000	110,000	115,000
Continuous current	600	600	600	600	400 600	600	600	600
Five-second capacity	30,000	30,000	30,000	23,000	11,000	30,000	30,000	30,000
Rupturing capacity, amp	5,300	5,500	5,500	5,200	5,030	8,000	8,000	8,000
Rupturing capacity, kva	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,500,000	1,500,000	1,500,000
Physical characteristics:								
Service	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor
Overall length	245 in.	280½ in.	283⅓ in.	226 in.	243⅞ in.	279 in.	299 in.	301⅜ in.
Overall width	82 in.	77⅞ in.	76 ⅞in.	83¾ in.	75 in.	90 in.	80⅜ in.	82⅜ in.
Overall height	186 in.	180½ in.	166½ in.	156¾ in.	145⅞ in.	188 in.	185½ in.	164½ in.
Height to top of tank	116 in.	110 in.	110 in.	106 in.	150 in.	118 in.	112½ in.	107¾ in.
Spacing between phases	72 in.	84 in.	84 in.	76 in.	71 in.	84 in.	90 in.	84 in.
Spacing between terminals	68 in.	69⅛ in.	78 in.	64 in.	50$\frac{13}{16}$ in.	68 in.	72⅜ in.	71 in.
Minimum ground clearance	....	....	36½ in.	35½ in.	....	....	....	36½ in.
Weight without oil	22,000	24,294	15,000	....	15,100	29,500	26,055	16,500
Weight of complete breaker	47,500	39,600	34,000	....	28,000	65,000	48,900	38,500
Tank:								
Shape	Round	Round	Round	Round	Round	Round	Round	Round
Type of bottom	Convex	Convex	Convex	Convex	Convex	Convex	Convex	Convex
Material	Welded steel	Welded steel	Welded steel	½-in. boiler plate	Welded steel	Welded steel	Welded steel	Welded steel
Material of top	Welded steel	Welded steel	Welded steel	½-in. boiler plate	Cast steel	Welded steel	Welded steel	Welded steel
Tank diameter	62 in.	54 in.	58 in.	66 in.	51$\frac{3}{16}$ in.	72 in.	60 in.	64 in.
Tank depth	102 in.	90 in.	96 in.	96 in.	76 in.	102 in.	92½ in.	95¾ in.
Gallons of oil per pole	1,135	750	830	1,133	600	1,600	1,015	1,032
Height of oil over contacts	....	....	40 in.	53¾ in.	43 in.	....	....	40⅛ in.
Location of manhole	In top	Side of tank	Side of tank	In top	Side of tank	In top of tank	Side of tank	Side of tank
Size of manhole	....	17 in.	20 in.	18 by 21 in.	17$\frac{11}{16}$ in.	....	17 in.	20 in.
Is tank liner used?	No	Yes	Yes	Yes	Yes	No	Yes	Yes
Bushing:								
Make	Westinghouse	General Electric	Locke or Ohio Brass	Ohio Brass	Am. Brown Boveri	Westinghouse	General Electric	Ohio Brass

Type	Condenser	Oil filled	Oil filled	Oil filled, Pat. No. 27,382	Oil filled	Condenser	Oil filled	Oil filled
Dry flashover	375 kv.	320	325	325	340	375	320	325
Wet flashover	330 kv.	250	256	220	240	330	250	256
Main contacts:								
Type	Butt	Rod and segment	Blade and jaw	Blade and jaw	Spherical butt	Butt	Rod and segment	Blade and jaw
Action	Plain break	Explosion chamber	Horiz. rotating	Horiz. linear	Plain break	Plain break	Explosion chamber	Plain break
Number per pole	2	2	6	6	10	2	2	6
Contact travel	$27\frac{1}{2}$	....	$15\frac{7}{8}$	13	$7\frac{7}{8}$	$27\frac{1}{2}$	....	$18\frac{3}{4}$
Total break	50	50	$72\frac{3}{4}$	63	$78\frac{3}{4}$	50	58	$91\frac{1}{2}$
Clearance to tank	....	....	$11\frac{1}{2}$	$7\frac{3}{4}$	$12\frac{1}{2}$	....	....	$11\frac{3}{4}$
Distance between contacts	....	....	$24\frac{3}{4}$	15	21	....	....	$29\frac{1}{2}$
Secondary contacts:								
Type	Butt	None	Sliding blade	Swinging butt	None	Butt	None	Sliding blade
Action	Quick break	....	Plain break	Plain break	....	Quick break	....	Plain break
Number per pole	2	....	6	6	....	2	....	6
Operator:								
Type	Solenoid *	Motor	Motor-wound spring	Motor or solenoid	Direct-geared motor	Solenoid ¶	Motor	Motor—wound spring □
Closing current	180	90–115	5.7	20 160	45	210	90–115	5.7
Tripping current	4.5	3	5.7	20 23	0.8	4.5	3	5.7
Operating voltage	125 d.c.	125 d.c.†	125 d.c.‡	110 125	125 d.c. or a.c.	125 d.c.	125 d.c. ○	125
Inch-pounds force	....	....	20,000	30,000 28,500	....	....	....	20,000
Is operator trip free?	Yes	Yes	Yes	Yes Yes §	Yes ‖	Yes	Yes	Yes
Operating characteristics:								
Dead time								
Opening time, no voltage								
Opening time, rated amp								
Closing time								
Contact rebound, inches								

* Motor available. † Motor can also be supplied for 250-v. d.c. or 220-v. a.c. 60 cycle. ‡ Motor 110–220 a.c., 125–250 or 24 d.c. § Solenoid mechanism requires a special "trip-free relay." ‖ Motor mechanism requires a special "trip-free relay." ¶ Motor available. ○ Motor can also be supplied for 250-v. d.c. or 220-v. a.c. 60 cycle. □ Motor 110–220 a.c. or 125–250 or 24 d.c.

220,000-VOLT OIL CIRCUIT BREAKERS

Manufacturer	Westinghouse	General Electric	Westinghouse	General Electric	Pacific Electric	Westinghouse	General Electric	Pacific Electric	Condit Brown Boveri
Type	G-11-S	FHKO-139-96YB-F6	G-22-AS	FHKO-139-108YC-F6	R-120	G-222-S	FHKO-139-103C-F7	R-120	BO-60-230
Rating:									
Voltage	187,000–220,000	137,000–220,000	187,000–220,000	187,000–220,000	187,000–220,000	220,000	220,000	220,000	230,000
Continuous current	600	600	600	600	600	600	600	600	400 600
Five-second capacity	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	11,000
Rupturing capacity amp.	3,300	5,200	6,600	6,600	6,600	6,600	6,600	6,600	6,300
Rupturing capacity, kva.	1,250,000	2,000,000	2,500,000	2,500,000	2,500,000	2,500,000	2,500,000	2,500,000	2,500,000
Physical characteristics:									
Service	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Outdoor
Overall length	350 in.	368 in.	530 in.	438⅝ in.	451½ in.	400 in.	438⅝ in.	451½ in.	429 in.
Overall width	114 in.	117 in.	131 in.	133¼ in.	132 in.	128½ in.	140 in.	132 in.	120 in.
Overall height	282 in.	257½ in.	282 in.	265 in.	264 in.	319 in.	280¼ in.	282 in.	300 in.
Height to top of tank	186 in.	160½ in.	186 in.	160½ in.	180 in.	186 in.	160½ in.	183 in.	170 in.
Spacing between phases	114 in.	120 in.	180 in.	144 in.	132 in.	122 in.	144 in.	132 in.	138 in.
Spacing between terminals	....	107 in.	....	114 in.	117 in.	112½ in.	130 in.	132 in.	103 in.
Minimum ground clearance									
Weight without oil	56,000	105,000	88,000	110,000	....	93,000	113,000	48,300	77,800
Weight of complete breaker	144,000	195,100	225,200	220,125	....	220,000	231,045	180,000	209,800
Tank:									
Shape	Elliptical	Round	Round	Round	Round	Round	Round	Round	Round
Type of bottom	Convex	Convex	Convex	Convex	Convex	Convex	Convex	Convex	Convex
Material	Welded steel	Welded steel	Welded steel	Welded steel	Welded steel	Welded steel	Welded steel	½-in. welded steel	Welded steel
Material of top	Welded steel	Welded steel	Welded steel	Welded steel	Welded steel	Welded steel	Welded steel	½-in. welded steel	Cast steel
Tank diameter	68 by 96 in.	96 in.	108 in.	108 in.	120 in.	108 in.	103 in.	120 in.	110 in.
Tank depth	170 in.	140½ in.	170 in.	140½ in.	167 in.	169½ in.	140½ in.	170 in.	146 in.
Gallons of oil per pole	3,910	3,960	6,100	4,850	5,950	5,660	5,202	5,800	6,130
Height of oil over contacts	....	....	....	....	....	....	....	66	89
Location of manhole	In top of tank	Side of tank	In top of tank	In top of tank	In top of tank	In top of tank	In top of tank	In top of tank	In side of tank
Size of manhole	....	22 in.	....	22 in.	19¼ by 27 in.	....	22 in.	19¼ by 27 in.	17$\frac{11}{16}$ in.
Is tank liner used?	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes

Bushing:									
Make	Westinghouse	General Electric	Westinghouse	General Electric	Locke	Westinghouse	General Electric	Ohio Brass or Locke	Am. Brown-Boveri
Type	Condenser	Oil filled	Condenser	Oil filled	Oil filled	Condenser	Oil filled	29,893 22,220	Oil filled
Dry flashover	570 kv.	535	570	535	535	665	610	650 610	700
Wet flashover	485 kv.	385	485	385	387	600	460	460 460	
Main contacts:									
Type	Butt	Rod and segment	Wedge and finger	Rod and segment	Blade and jaw	Butt	Rod and segment	Blade and jaw	Spherical butt
Action	Plain break	Explosion chamber	Plain break	Explosion chamber	Horiz. rotating	Plain break	Explosion chamber	Horiz. rotating	Plain break
Number per pole	2	2	2	2	6	2	2	6	10
Contact travel	42	...	42	...	72 deg.	44	...	33	33
Total break	84	82	84	82	147 in.	84	82	147	330
Clearance to tank	...	...	...	...	28½ in.	...	...	23½ in.	50 in.
Distance between contacts	...	...	...	...	45 in.	...	...	48½ in.	39 in.
Secondary contacts:									
Type	Butt	None	Butt	None	Sliding blade	Butt	None	Sliding blade	None
Action	Plain break	...	Quick break	...	Plain break	Quick break	...	Plain break	
Number per pole	2	...	2	...	6	2	...	6	
Operator:									
Type	Solenoid	Motor	Solenoid	Motor	Motor-wound springs	Solenoid	Motor	Motor-wound springs	Direct-geared motor
Closing current	210	160–200	239	160–200	5½	150	160–200	5½	120
Tripping current	4.5	3	4.5	3	5½	5	3	5½	
Operating voltage	125 d.c.	125 d.c.*	125 d.c.	125 d.c.*	125 d.c.†	125	125 d.c.*	125 d.c.†	
Inch-pounds force	...	...	...	...	16,000	...	...	20,000	125 d.c. or a.c.
Is operator trip free?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes §
Operating characteristics:									
Dead time									
Opening time, no voltage									
Opening time, rated amp									
Closing time									
Contact rebound, inches									

* Motor can also be supplied for 250-v. d.c. or 220-v. a.c., 60 cycles. † Motor current 24 amp. at 125 volts. § Trip-free action obtained with special "trip-free relay."

CHAPTER XIV

FOREIGN HIGH-VOLTAGE OIL CIRCUIT BREAKERS

PRACTICALLY all high-voltage oil circuit breakers in use on the transmission systems now operating in the United States are American-made breakers. What exceptions there are to the above statement may usually be set down as experimental breakers purchased by American companies to test out European designs.

There are several reasons for the preference for American-made breakers, the principal one being that the American utilities have led the world in high-voltage transmission and the design of breakers has had to keep pace with the increasing demands for higher voltages and greater rupturing capacities. European designs have not been such as could effectively compete with the breakers offered by American manufacturers to meet the requirements of American users. Tariff and working agreements between American and affiliated European manufacturers are other factors influencing the purchase of foreign-made breakers by American users.

Both the General Electric Company and the Westinghouse Electric and Manufacturing Company have manufacturing agreements with companies throughout the world, these agreements taking the form of interchange of patents and designs. As a result, the products of the affiliated foreign manufacturers take on the general characteristics of the American breakers and differ in detail rather than in general appearance.

The General Electric Company has manufacturing agreements with the British Thompson–Houston Company as well as with the corresponding French and Italian com-

panies. In Germany, the affiliation is with the Allgemeine Elektrizitäts Gesellschaft, and, in Japan, the Shibaura Engineering Works.

The Westinghouse Company has a German affiliation with the Siemens-Schuckert Werke and a Japanese affiliation with the Mitsubishi Company and for a time maintained British, French, and Italian Westinghouse companies for the manufacture of their equipment in foreign countries. In England, the Metropolitan-Vickers Company took over the British Westinghouse Company, and the "Metrovick" high-voltage oil circuit breakers retained the general appearance of the Westinghouse breakers. Recently, the Metropolitan-Vickers was acquired by the British Thompson-Houston Company, and it will be interesting to note the modifications which the General Electric affiliation will bring about in the Westinghouse designs.

In Switzerland, the Brown Boveri and the Oerlikon companies have done a great deal of high-voltage oil circuit breaker work. The former company has been the most important European competitor in the American market. The American Brown Boveri Company, while a distinct organization from the original Swiss company, is very closely allied with the parent organization, and the equipment designs used in the American factories are essentially the same as those used in Switzerland. The high-voltage oil circuit breakers built in Switzerland are very similar to the type BO-60 breakers of the American Brown Boveri Company described elsewhere in this text.

It is not intended to describe the high-voltage oil circuit breaker practice of the various foreign manufacturers at any length because of the space limitations of this book. A few brief discussions, however, to set forth the general trend of European design and the principal points of difference from the American practice will be of interest.

As would be naturally expected, the product of those companies having manufacturing agreements with the American companies is very similar in design and appearance.

The Metrovick breakers are almost identical with the Westinghouse breakers, and, in fact, the same type designations, such as G–11, G–22, etc., are used. The familiar condenser-type bushing is standard, and to all appearances the breaker might have come from the American works of the Westinghouse Company.

The breakers of the British Thompson–Houston Company depart more from the General Electric Company designs than was the case with the Metrovick breakers. The design of the explosion-chamber contacts is practically the same, but there is a difference in the type of operating mechanism and the shape of the tank covers, and no round-tank breakers are built. The French breakers, built by the Compagnie Française Thompson–Houston, follow the General Electric designs almost exactly. French engineers have been very progressive and have kept in constant touch with the latest designs in high-voltage transmission. Several groups of French engineers have visited the United States and particularly the Pacific Coast for the purpose of studying the 220-kv. transmission systems in operation there.

The Siemens–Schuckert Werke in Charlottenburg has produced some 220-kv. breakers for use on the German transmission lines of that voltage. Details of the contact mechanisms are not available. The pole spacing of the breakers is 16 ft. $4\frac{7}{8}$ in. They are 26 ft. $8\frac{3}{8}$ in. in height from rail to top of bushing, with a bushing height of approximately 9 ft. 6 in. Outside tank diameter is 8 ft. $10\frac{1}{4}$ in., and the weight of the complete breaker, including oil, approximately 197,000 lb. They are motor operated, but the details of the motor mechanism are not available. The bushings in these breakers are of the condenser type with porcelain rain sheds and are equipped at the top with a metal ring for the suppression of corona. Each tank is fitted with an air-vent pipe for the purpose of relieving excessive pressures.

The equipment built by European manufacturers which

are independent and unaffiliated with the American companies shows a wide range of variation from American practice. Practically all of the high-voltage oil circuit breakers of these independent companies are of the multibreak contact type and employ a resistance or reactance in

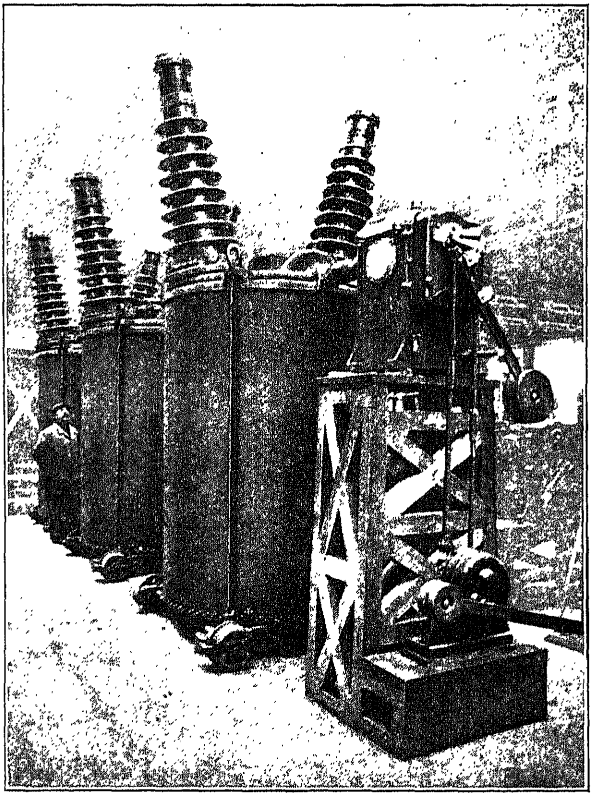


FIG. 70.—Delle HE-11, 120-kv. oil circuit breaker.

series with one or more pairs of contacts to reduce the current before the final interruption. A 120,000-volt breaker built by the Ateliers de Constructions Electriques de Delle, Paris, France, is shown in Fig. 70. With the exception of the operator, the breaker has somewhat the same general appearance as an American breaker of the same voltage

rating. The wheels on each tank are characteristic of the European-built breakers. The Delle breaker, shown in Fig. 70, is known as "type HE-11" and is rated for use on a system operating at 120,000 volts. The 75,000-volt breaker is known as the "type HE-9." These breakers are of the multibreak six-contact type and have wedge-and-finger type contacts. One pair of contacts short circuits a

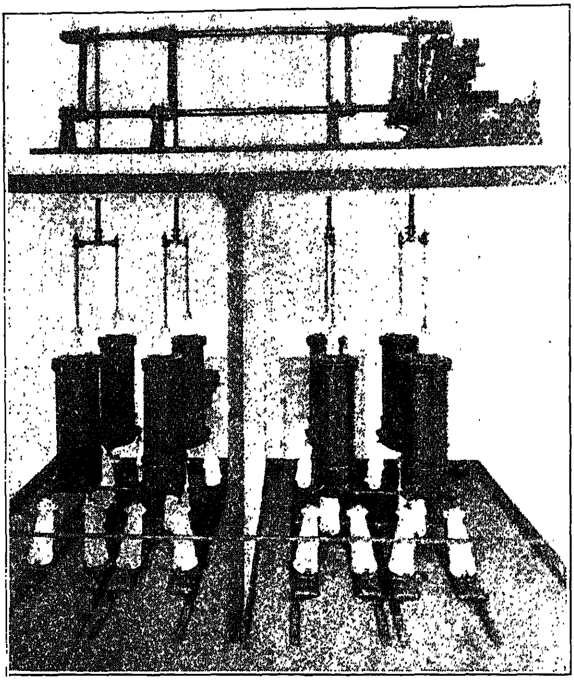


FIG. 71.—Oerlikon 60-kv., four-break oil circuit breaker.

resistance which is introduced into the circuit as the breaker opens. The contact arrangement is much the same as the Voigt and Haeffner breaker shown in Fig. 74. Bushings are of the oil-filled type.

A 60,000-volt, single-phase oil circuit breaker built by Oerlikon and installed in the Ritom Station near the Saint Gothard tunnel, Switzerland, is shown in Fig. 71. The breaker resembles, somewhat, the General Electric Company

type H breakers for 15,000-volt service in that it has an upward instead of a downward break, as usual in high-voltage breakers. They are, however, four-break instead of two-break breakers, as is the case with the General Electric Company ones. They are solenoid operated and have the usual current-limiting resistance arrangement common to the European breakers, but of a rather unique character, as shown in Fig. 72.

The upper diagram, marked 1, shows the contact arrangement with the breaker in the full-open position. As the

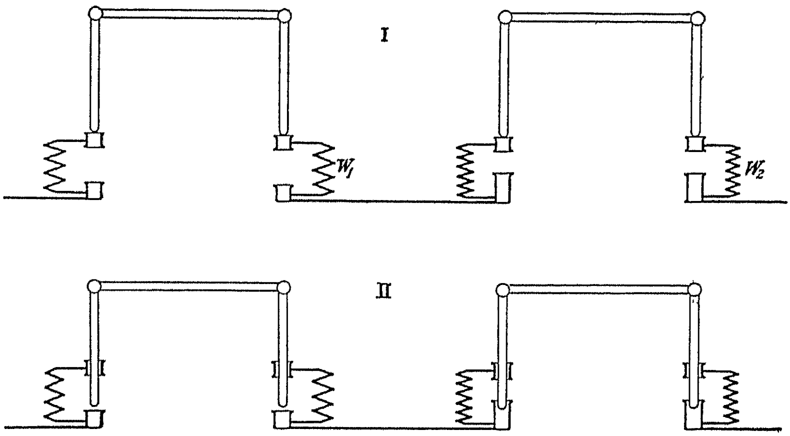


FIG. 72.—Details of contact arrangement in Fig. 71.

breaker starts to close, the bayonet contacts move downward and enter the upper ring contacts and insert resistances $W1$ and $W2$ in the circuit. The next step in the closure is shown in the lower diagram, marked II, in which the right-hand pair of bayonets have entered the bottom ring contacts, thus short circuiting resistance $W2$. Resistance $W1$ is still in circuit but will be short circuited when the switch is fully closed and the left-hand bayonets have also entered their lower ring contacts. In opening, the reverse action takes place and a progressively increasing resistance is introduced into the circuit until the breaker is fully opened. No data are available as to the operation

of these breakers, but they are used for the protection of a railway load subject to frequent disturbances and presumably meet the requirements of the system upon which they are installed. It is doubtful if a high kilovolt-ampere interrupting capacity is required, as the system is not so extensive as some of those to be found in America.

One of the principal manufacturers of high-voltage oil circuit breakers in Italy is the Compagnia Generale di Elettricita, which, as may be supposed from its name, is affiliated with the General Electric Company. The breakers manufactured in Italy by this company follow, in general, the General Electric designs, but some modifications have been made to adapt them to special requirements, notably the addition of resistors to reduce current before final break.

The German high-voltage oil circuit breakers show the widest departure from American practice, even in those companies which are affiliated with the American ones. The Allgemeine Elektrizitäts Gesellschaft (A. E. G.) is very closely allied with the General Electric Company but does not follow the General Electric designs in the manufacture of high-voltage oil circuit breakers. A single-pole element of a typical 110,000-volt A. E. G. breaker is shown in Fig. 73. The explosion type of contact is used but the usual European resistance has been added to the breakers and is housed in the insulated cylinder at the bottom of the breaker. The moving contacts travel along bakelite-paper tube guides in a manner quite different from American practice. In addition to the main explosion-chamber contacts, there is an auxiliary contact for short circuiting and cutting in the "charging resistance." On indoor breakers, the bushings are of "Geax," a bakelite-paper product, and have no porcelain housing. Outdoor bushings are protected from the weather by a shell of porcelain. The highest rupturing-capacity rating given to any of the high-voltage A. E. G. breakers is 500,000 kva., which would make them entirely unsuited for use on the large American transmission networks.

Another German breaker is shown in Fig. 74. This is the product of Voigt und Haeffner Aktien–Gesellschaft, Frankfurt-am-Main, and represents another type of German breaker. This is a multibreak six-contact breaker, using a wedge-and-finger type of contact in which the outside con-

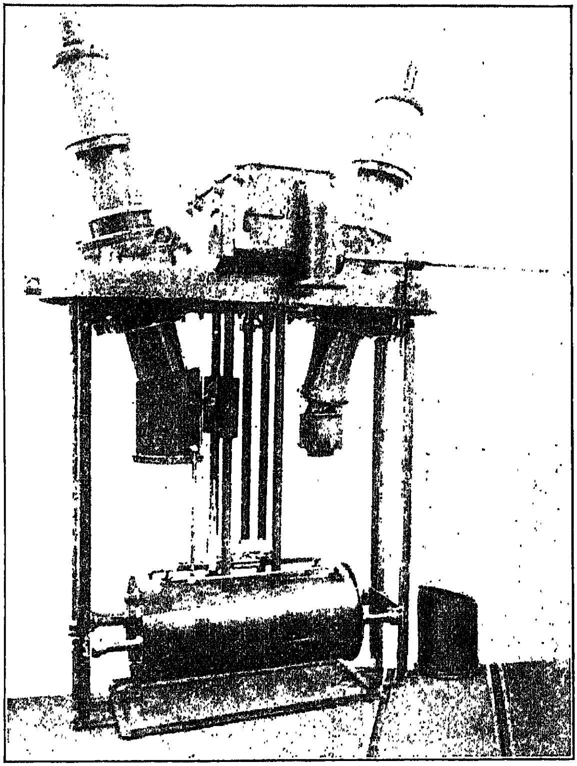


FIG. 73.—A.E.G. 110-kv. oil circuit breaker with both explosion pots and limiting resistors.

tacts are longer than the others and form a pair of contacts to complete the final break through a resistance. They are well placed in the breaker so as to bring about the interruption of the arc in the most favorable location, and if the operating mechanism is of such design as to give a high speed of break, the switch should be quite satisfactory in service.

The Voigt and Haeffner operating mechanism is worthy

of special mention, as it is of the motor-wound, spring-actuated type, similar, in some respects, to the type MW operator of the Pacific Electric Manufacturing Corp., previously described. The springs operate only to close the breaker, and it is opened by the action of gravity assisted by small compression springs. One point of criticism lies in the fact that the closing springs are held in tension when set to operate the breaker, and a broken spring would

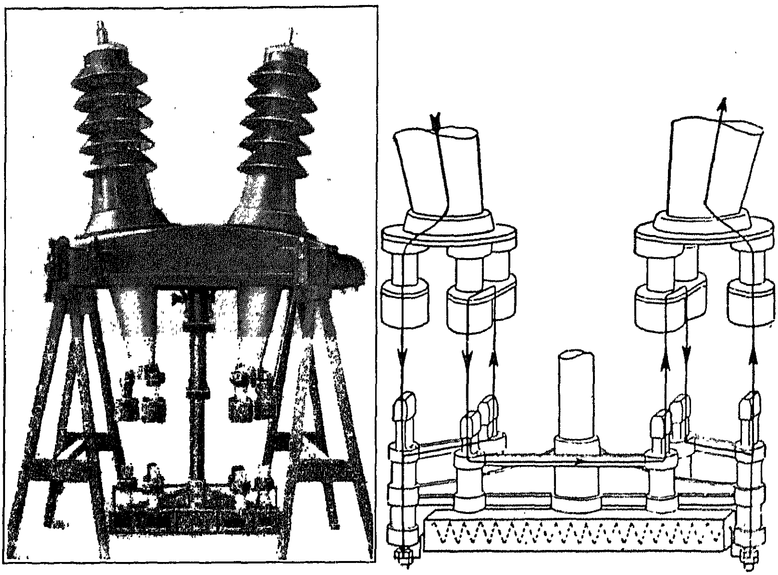


FIG. 74.—Voigt and Haeffner, 110-kv. oil-circuit-breaker details and contact arrangement.

render the mechanism inoperative. It is regretted that no data are available as to the operation of this device, as it would be interesting to compare it with the American-made product and note the speed of operation and amount of energy available for the closing of the breaker upon the release of the springs. It is probable that still better breaker operation could be obtained if a second set of springs were added to open the breaker, and thus, give an increased speed of break.

As a general summing up of European high-voltage circuit-breaker practice, it may be stated that the breakers are not of the high interrupting-capacity type to be found in American designs. Very few have cylindrical tanks, which are essential to resist the pressures developed when rupturing heavy currents, and, for the most part, the operating mechanisms are weak and unsuited for heavy-duty requirements. The multibreak type of contact predominates, and almost all breakers employ the current-limiting resistance. Where there is any marked similarity to the breakers of American design, it may generally be traced to an affiliation of companies and an exchange of designs.

The operating mechanisms are, in general, not of the trip-free type. As has been frequently noted, this is an essential requirement on breakers which will be subjected to line-testing duties. The breakers are not provided with oil-separating chambers to permit of venting at times of severe service requirements and, at the same time, prevent the throwing of oil. It is questionable as to whether the majority of the foreign-made breakers could pass the OCO + OCO duty cycle specified by the American test requirements. The rapid growth of high-tension transmission systems throughout Europe will bring with it a great improvement in high-voltage oil circuit-breaker design to meet the increasing demands for rupturing capacity which will naturally accompany this growth. It is probable, however, that American utilities will continue to favor the American-made product, due to the greater experience in manufacture and design backed up with many installations of breakers which have successfully met operating requirements.

CHAPTER XV

TERMINAL BUSHINGS

THE first oil circuit breakers to be placed in service were designed for what is today considered low voltage, and the early breakers for service at voltages of 15,000 and under received universal attention from engineers. For this class of service, the porcelain parts available at the time afforded adequate insulation, and practically all breakers were insulated by means of solid porcelain.

As the voltages of transmission lines became higher, the requirements for oil circuit breaker bushings of increasingly higher insulating values placed demands on the porcelain manufacturers which the art at that time did not permit of ready fulfillment. As a result, the major portion of the pioneer high-voltage breakers (60 kv. and above) had bushings built up of various materials. This was particularly true of those breakers built in the field by the personnel of operating companies whose facilities and material resources were limited. The original Stanley 60-kv. breaker, however, used solid-porcelain bushings mounted in a cast-iron tank cover, a type of construction not adopted by other manufacturers until several years later.

With the growing demand for high-voltage breakers came various methods of meeting the bushing problem. The Westinghouse Company built up their bushings from mica and tape of various kinds. The General Electric Company, using the type H form of breaker shown in Fig. 16, insulated the tanks so that, in the strictest sense, there were no terminal bushings. This sufficed for equipment to be used at voltages of 80,000 and under.

About 1906, the demand for higher transmission-line insulation was met by the development of the suspension-type insulator, and the oil circuit breaker insulation problem again became acute. With the higher transmission voltages came the demand for outdoor switching equipment, and new bushing designs had to be developed.

The Westinghouse Company began an investigation of the practical manufacturing methods required to produce the condenser type of terminal bushing proposed by Rudolph Nagel (45). The result of this work was presented in a paper before the A. I. E. E. (46), and the condenser type of bushing was adopted and has been in general use by the Westinghouse Company since that time.

At the same time, the General Electric Company developed a compound-filled bushing made up of cylinders of fiber or paper held apart by spacers and enclosed in an oil-tight casing made up of fiber rings and washers. Such bushings were used in the type K–10 breakers shown in Fig. 21.

Both the condenser type and the compound-filled type were subsequently covered with porcelain rain sheds and are the forerunners of the modern bushings now being furnished by the two companies. A waterproof housing was essential to fit these bushings for outdoor use, and porcelain has proved the best material for this purpose. In the development of the technique necessary to produce these porcelain rain sheds in the factories of the porcelain manufacturers, a third type of bushing was finally perfected. It is a modification of the General Electric oil-filled bushing in which the fiber insulating tubes are replaced by a fewer number of porcelain tubes. This type of bushing is represented by the present-day product of the Ohio Brass Company.

There are, thus, three distinct types of high-voltage entrance bushings at present available for use in oil circuit breakers. They may be classified as follows:

1. Solid porcelain.
2. Condenser type.

3. Oil-filled type.
    a. With micarta, herkolite, or paper insulating tubes.
    b. With porcelain insulating tubes.

In all types the problem is to bring a conductor at high potential through a grounded plate. If that part of the plate next the conductor be thickened into the form of a band giving the usual construction, the capacity between the band and the conductor in air is $\frac{1}{2 \log_e \frac{R_b}{R_c}}$, where R_b = radius of the band and R_c = radius of the conductor. If E represents the charge on the conductor per unit length, the potential distribution will be $2E \log_e \frac{R_b}{R_c}$. This results in a potential gradient highest next the conductor.

When materials other than air are introduced into the field, the lines of force are displaced in a fashion depending on the dielectric constant of the material. For materials of high dielectric constant, the lines are crowded toward the dielectric, the gradient thereby increased, and corona formation and breakdown occurring unless proper precautions are taken.

It is thus possible, as has been pointed out a number of times, to change the gradient by changing the dielectric in steps of dielectric constants, but the few dielectrics available with suitably stepped constants make the practical application very difficult.

The solid porcelain, and, to a great extent, the oil-filled bushings, accept the field formation and depend for their success on the insulation qualities of the dielectric to withstand the unequal strain set up within it. Condenser bushings, on the other hand, accommodate the dielectric to the flux distribution. The original principle called for the condition where the field intensity times the radius times the metal-layer length was constant, and the ends of the metal sheaths formed a hyperbola with the conductor as an

asymptote. The later development, and that along which American designs are built, calls for equal axial stress and allows unequal radial stress. In this design the capacity between the metal layers is constant, and the layers have lengths arranged in arithmetical progression. The steps of insulation vary in thickness in such a fashion that if thickness is plotted against number of steps, the resulting curve approximates an hyperbola.

The metal used in American and English practice is tinfoil, but some Continental bushings are built with copper-wire mesh. Some Continental manufacturers, also, form their condenser bushings from metal-clad insulating cylinders, though the product is usually considered inferior to the built-up bushings.

In all high-tension bushing design, some control of the flux is exercised by virtue of the different materials used, while occasional instances of specific control are evident, such, for instance, as the internal metallic shield used on the Ohio Brass Company oil-filled bushings and the metallic collar extending below the oil level on the General Electric, Westinghouse, and Locke bushings. Some such form of flux control is essential, on account of the fact that the flux will crowd from the air into the higher permittivity oil and there will be a very much higher gradient at the oil surface than in the air above, starting corona at very much lower voltages than where the metallic parts extend below the oil surface.

The theoretical length under oil is approximately one-third that above, since the oil has about three times the dielectric strength of the air. Additional length is required above to compensate for dirt and moisture, however, so that no general design law can be laid down.

SOLID-PORCELAIN BUSHINGS

There is, at the present time, no well-defined line representing the upper limit in voltage at which the solid-porce-

lain type of oil circuit breaker bushing should be used. All manufacturers use them for outdoor service at the lower voltages, and at least three circuit breaker manufacturers have standardized on solid porcelain for 60,000-volt breaker bushings. None, however, use them on 110,000-volt breakers except for very special installations. They are, in general, made up from tubes of porcelain, with rain sheds or petticoats on the outer tube. There are three general classes, according to manufacturing technique:

1. Tubes extruded from a pug mill and turned in a lathe.
2. Tubes built up on a potter's wheel.
3. Tubes moulded on the inside of porous casts.

In general, the petticoats can be fashioned with the tube by

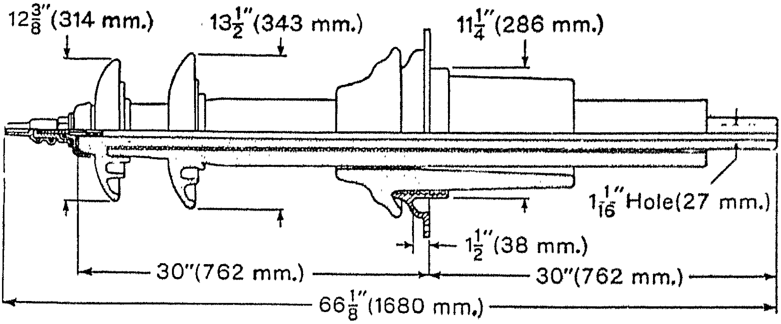


FIG. 75.—Ohio Brass Company porcelain entrance bushing for 77,000 volts.

either process, or they may be moulded separately and attached (*a*) by wetting and working together on the tube or (*b*) by glazing on.

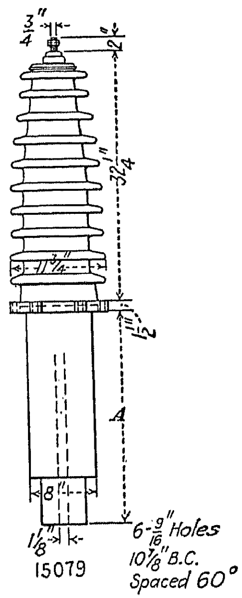
No operating evidence has been presented discriminating between these methods. In fact, more than one is usually in use at each of the several factories at the same time.

Since approximately 1920, no general criticism of the porcelain itself has been offered. All controversies have been on design features and not on material, as was the case before that time.

Figure 75 represents a three-part porcelain insulator as manufactured by the Ohio Brass Company for 77-kv.

service. Figure 76 represents a similar type supplied by the Locke Insulator Company.

Some of the later European breakers are equipped with steatite bushings, for which much can be said if the smaller samples in the United States may be taken as a criterion. Steatite is not glazed, however, and presents a rough surface for weathering and dirt collection. The flashover and leakage characteristics are much the same for all types and will, therefore, be taken up as a whole.



Number	15079
[illegible]	73,000
[illegible]	240,000
[illegible]	200,000
Max. Size Copper Cable	400,000 cm.
Net Weight	235 Lbs.
Packed Weight	300 Lbs.
Standard Package	Crate of 1
Code Word	RIBTU
Weights based on "A" being	27

FIG. 76.—Locke porcelain entrance bushing for 73,000 volts.

CONDENSER-TYPE BUSHINGS

The condenser type of high-voltage bushing has been developed in America by the Westinghouse Electric and Manufacturing Company and is furnished in practically all high-voltage equipment manufactured by that company. The underlying theory of this type of bushing construction was published as early as 1906 (47), and its value for use in high-voltage equipment was at once recognized. The mathematical treatment was presented before a convention of the A. I. E. E. by an engineer of the Westinghouse Company in 1909 (48). Fundamentally, it is a method of dividing up the potential on properly proportioned condenser plates and handling a part of the total potential on each condenser section. The practical difficulties in manufacture are the extreme care and carefully controlled conditions required to produce the finished product. Careful selection is required as regards rating. Where failures have occurred,

the cause can usually be traced to underrating or deteriorated surface conditions. Properly rated and with attention paid to the condition of their surface, their service record is excellent.

This type of bushing is very sensitive to surface conditions, and special precautions must be taken when they are used in oil circuit breakers, where dirty oil and carbon deposits may cause surface leakage and ultimate breakdown. It is, therefore, customary in oil circuit-breaker installations to encase the lower end of the bushing in a porcelain shield, which serves the double purpose of protecting the bushing against damage by the arc, and also, acts as an oil-filled housing full of clean oil to prevent leakage between condenser plates over the ends of the condenser insulation. Since the leakage distance required under oil is approximately one-third that required in air, the lower ends of oil circuit-breaker bushings are commonly made shorter than the tops. In condenser bushings, this results in closer spacing of the ends of the metallic tubes, and dirty oil causes trouble from conducting paths over the dielectric, so that, for use in oil circuit-breaker work, condenser bushings are covered with an arc shield of porcelain filled with clean oil when installed. Figures 77, 78, and 79 show the Westinghouse arc-shield assembly for a 220-kv. bushing.

This type of bushing enjoys a particular advantage when used in high-voltage equipment, due to its relatively small diameter. Owing to the cost of extremely high-voltage current transformers, it has become usual practice to make use of bushing-type current transformers for relay operation, thus combining the current transformer with the oil circuit breaker. The characteristics of the bushing-type current transformers depend, to a large extent, on their iron section, and since bushings of the condenser type are small in diameter compared to other types, current transformers with much better characteristics can be built around them than is possible with the larger-diameter bushings.

The condenser-type bushing is, also, a more rugged piece

of equipment than the oil-filled bushing and will withstand greater mechanical strains. If the porcelain housing of the bushing is cracked or broken, the bushing is not necessarily rendered unusable, and the apparatus on which it is installed

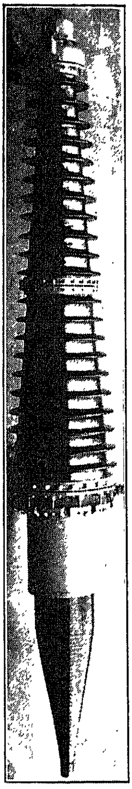


FIG. 77.—Condenser bushing for 220-kv. oil circuit breaker with arc shields and fittings removed, Westinghouse Company.

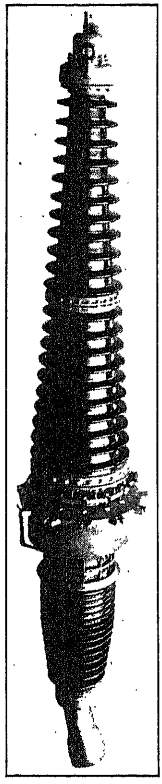
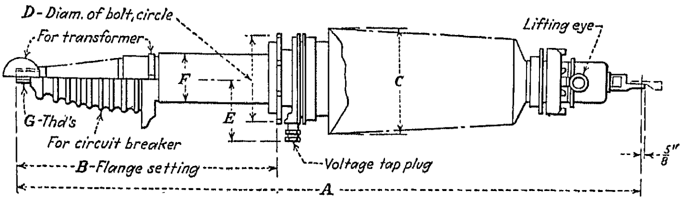


FIG. 78.—Condenser bushing for 220-kv. oil circuit breaker, Westinghouse Company.

may be continued in service provided weather conditions are such that moisture will not be admitted to the condenser sections. The porcelain housing serves only to keep the bushing dry and clean and is not essential to its insulating qualities. A Westinghouse bushing for 220-kv. service is shown in Figs. 77 and 78, the former being of a bushing with



KV	A	B	C	D	E	F	G	Wt.	No. of Rain Sheds
88	$90\frac{15}{16}$	$37\frac{5}{8}$	$15\frac{11}{16}$	$11\frac{1}{8}$	$8\frac{5}{8}$	7	2″ –12	414	7
110	$101\frac{7}{8}$	$39\frac{5}{16}$	$16\frac{3}{4}$	$13\frac{1}{8}$	$8\frac{5}{8}$	$8\frac{3}{4}$	2″ –12	560	9
132	$113\frac{13}{16}$	$42\frac{3}{8}$	$17\frac{13}{16}$	$15\frac{3}{4}$	$8\frac{5}{8}$	$10\frac{1}{4}$	$2\frac{1}{4}$″–12	750	11
154	$122\frac{3}{8}$	$44\frac{1}{8}$	$18\frac{7}{8}$	$15\frac{1}{2}$	11	$10\frac{3}{4}$	$2\frac{1}{4}$″–12	825	13
187	$153\frac{1}{2}$	52	$22\frac{7}{8}$	$19\frac{7}{8}$	$13\frac{1}{2}$	$14\frac{1}{2}$	3″ –12	1300	16
220	$194\frac{1}{2}$	$69\frac{7}{8}$	$26\frac{1}{2}$	$23\frac{1}{2}$	16	$17\frac{1}{8}$	$3\frac{1}{4}$″–12	2800	21

FIG. 79.—Condenser-bushing dimensions, Westinghouse Company.

TABLE VII.—ONE-MINUTE AND FLASHOVER VALUES FOR STANDARD OUTDOOR CONDENSER BUSHINGS

Volt class, kv.	Standard minute test,[1] kv., Dry	1-min. rain, kv. hold value, Wet	Average flashover value, kv. Dry	Average flashover value, kv. Wet
Max. 50.	127.5	120.	190.	160.
73.	183.	170.	225.	190.
88.	250.	220.	300.	270.
110.	300.	275.	375.	330.
132.	350.	315.	420.	360.
154.	410.	360.	480.	405.
187.	500.	410.	570.	485.
220.	600.	515.	665.	600.

[1] A. I. E. E. values for 5000-ft. altitude.

The flashover values are those obtained at the works. Sea-level values will be approximately 3 per cent higher.

the arc-shield assembly removed to show the stepping of the condenser layers. Figure 79 gives a table of dimensions for various voltage ratings of Westinghouse condenser bushings.

The general conclusion regarding bushing ratings applies to condenser types as well as others and will be considered in the summary.

OIL-FILLED BUSHINGS

Moulded Insulating-tube Type.

The original oil or compound-filled bushings were designed for indoor use only and were built up of concentric paper or fiber sleeves or cylinders with the space in between filled with oil or one of a number of resinous compounds. The outside shell was made up of rings of fiber and flat washers of the same material shellacked together. Bushings of this type are illustrated in the switches shown in Figs. 19, 20, and 21. The principal difficulty encountered in the manufacture and use of bushings of this type was the maintenance of an oil-tight housing. Being of a built-up construction, it was extremely difficult to prevent leakage. The viscous compounds which were tried as substitutes for oil were not fully satisfactory, and the bushings gave considerable trouble, although a great many of this type are still in use after approximately 20 years of service.

When the demand for outdoor oil circuit breakers arose, about 1910, the built-up outer covering of the bushing was replaced by a porcelain shell, and thus originated the type of oil-filled bushing now being produced by the General Electric Company. It was much easier to make the porcelain shell oil-tight, and, consequently, the use of compounds as fillers was abandoned in favor of the familiar insulating oil.

The General Electric Company manufactures a standard line of oil-filled bushings varying in voltage rating from 50 to 220 kv. The characteristics are given in Tables VIII

and XI, and a typical bushing is shown in Figs. 80 and 81. The construction consists essentially of a middle section, which is a cylindrical metallic casting with a flange at either end. It is this section which is attached to the tank of the oil circuit breaker. The upper section of the bushing is made of one-piece petticoated porcelain, except in the 187- and 220-kv. bushings, in which the upper section con-

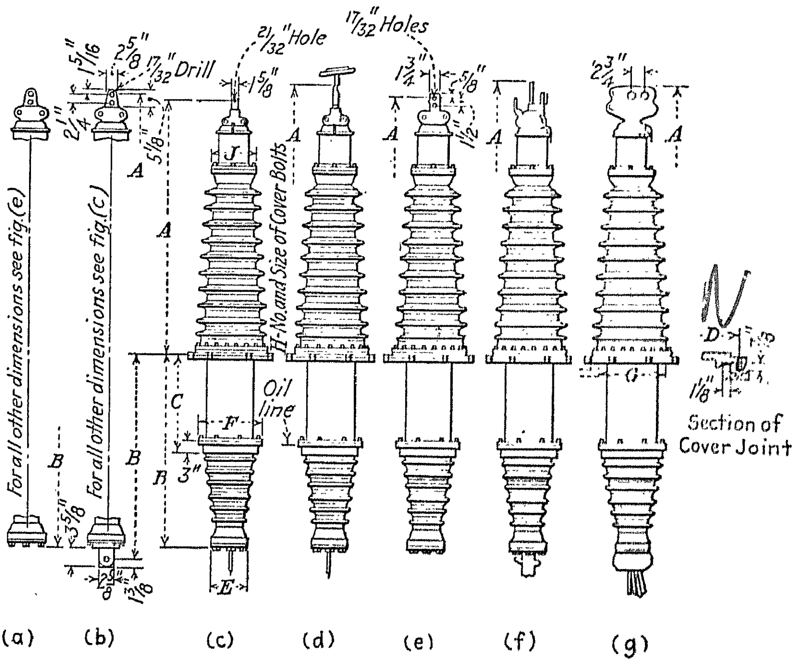


FIG. 80.—Typical line of General Electric bushings.

sists of two porcelain shells joined by clamping rings with a gasket between to make an oil-tight joint. There are no cemented joints between porcelains. The bottom of the top section is cemented to a flange and bolted to the central casting. The bottom section is a single piece of corrugated porcelain similarly attached to the central casting.

The interior of the shell contains a number of concentric insulating cylinders of varying length and made of herkolite,

a very strong insulating material made of paper wrapped on a form and impregnated with a phenolitic condensate which solidifies and unites the entire structure into a homogenous mass when subjected to heat and pressure.

A copper tube extends through the center of the bushings, and the oil space between this central conductor and the external shell is broken up into concentric ducts by the insulating cylinders. A large glass gage is mounted on the top of the bushing to provide for expansion of the oil in the bushing and to afford visual evidence that there is sufficient oil in the bushing.

This type of bushing has a full oil circulation, which results in a lower operating temperature and a continuous change of the dielectric at the points of highest voltage stress. Internal air pockets and consequent corona are prevented by the use of a fluid insulation. On the other hand, the use of a fluid insulation requires complete oil tightness in all joints to prevent leakage if the integrity of the insulation is to be maintained. The porcelain structure is very substantially built and will withstand some mechanical shock without injury. Great care, however, must be exercised in the use of oil-filled bushings to prevent injury to the porcelain shell, because the equipment cannot be continued in service if the porcelain shell is cracked sufficiently to cause oil leakage.

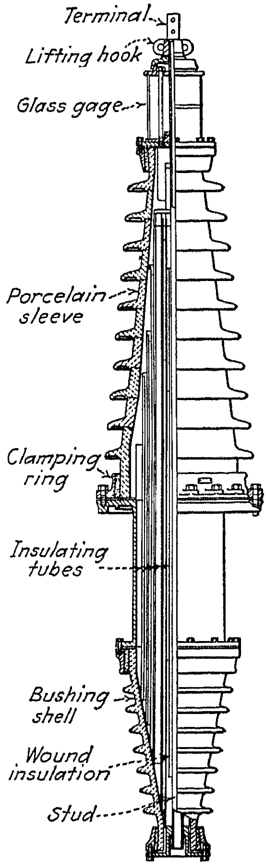


FIG. 81.—Details of General Electric bushing.

Bushings manufactured by the Locke Insulator Company

TABLE VIII.—TYPE OFT, FORM B

Max. current, amp., bushing only	Class	Approx. net weight	Dimensions								
			A	B	C	D	E	F	G	H	J
400	F-1	500	4'1-$\frac{13}{16}$"	3'4-$\frac{1}{4}$"	22-$\frac{11}{16}$"	8-$\frac{3}{16}$"	8-$\frac{3}{4}$"	12-$\frac{3}{4}$"	13-$\frac{1}{4}$"	6-$\frac{3}{4}$"	8-$\frac{5}{8}$"
400	F-2	730	4'9-$\frac{13}{16}$"	3'8-$\frac{3}{4}$"	22-$\frac{11}{16}$"	9-$\frac{7}{16}$"	8-$\frac{3}{4}$"	14-$\frac{1}{2}$"	15-$\frac{3}{4}$"	9-$\frac{3}{4}$"	10-$\frac{3}{4}$"
400	F-3	1,010	5'5-$\frac{7}{16}$"	4'$\frac{1}{4}$"	22-$\frac{11}{16}$"	10-$\frac{3}{8}$"	8-$\frac{3}{4}$"	17"	17-$\frac{5}{8}$"	9-$\frac{3}{4}$"	10-$\frac{3}{4}$"
400	F-4	1,290	5'11-$\frac{13}{16}$"	4'3-$\frac{3}{4}$"	22-$\frac{11}{16}$"	11-$\frac{7}{16}$"	8-$\frac{3}{4}$"	19-$\frac{1}{8}$"	19-$\frac{3}{4}$"	9-$\frac{3}{4}$"	10-$\frac{3}{4}$"
400	F-5	1,950	6'6-$\frac{15}{16}$"	5'$\frac{1}{4}$"	2'3-$\frac{11}{16}$"	12-$\frac{3}{4}$"	8-$\frac{3}{4}$"	21-$\frac{1}{8}$"	22-$\frac{3}{8}$"	12-$\frac{3}{4}$"	13-$\frac{1}{2}$"
400	F-6	2,485	7'8-$\frac{7}{16}$"	5'7-$\frac{5}{16}$"	2'7-$\frac{11}{16}$"	14-$\frac{1}{4}$"	14-$\frac{7}{8}$"	2'$\frac{1}{4}$"	2'1-$\frac{1}{2}$"	12-$\frac{3}{4}$"	13-$\frac{1}{2}$"
400	F-7	3,260	8'10-$\frac{5}{8}$"	5'11-$\frac{13}{16}$"	2'7-$\frac{11}{16}$"	16"	14-$\frac{7}{8}$"	2'3"	2'4-$\frac{7}{8}$"	12-$\frac{3}{4}$"	13-$\frac{1}{2}$"

TABLE IX.—LOW-ALTITUDE BUSHINGS

Class	Guaranteed arcover (sea level), kv.		Standard 1-min. hp. (sea level) test, kv.		A. I. E. E. rating, kv.	
	Dry	Wet	Dry	Wet	Sea level	4,000 ft.
F-1	270	215	250	200	110	97
F-2	320	250	300	230	132	116
F-3	375	280	350	260	154	135
F-4	430	310	400	290	177	155
F-5	480	350	450	325	199	175
F-6	535	385	500	360	221	194
F-7	610	460	565	430	250	220

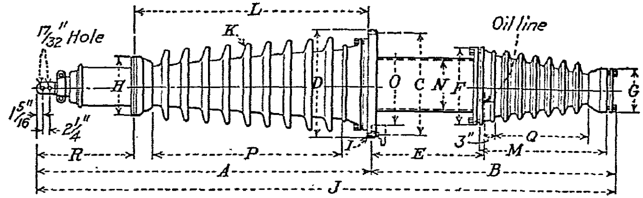
have the same general characteristics as those of the General Electric Company. Their principal dimensions are shown in Fig. 82.

Porcelain Insulating-tube Type.

In America, the principal manufacturers and advocates of the all-porcelain oil-filled type of bushing are the Ohio Brass Company and American Brown Boveri Company. Figure 83 is a typical example of this type of oil-filled bushing for use at 110,000 volts as manufactured by the Ohio Brass Company.

The Ohio Brass Company's oil-filled porcelain-insulated bushings are, by comparison, larger in diameter than the types previously described and are further distinguished by having an internal shield extending to a point below the oil level, which makes unnecessary a metallic covering. The large diameter reduces the dielectric stress and so reduces the tendency to coat the surface of the porcelain with the conducting particles which may be carried in the oil. These particles tend to follow the electrostatic field which terminates at the bushing and to be there deposited. The

OUTLINE. DATA SHEET.—BUSHING, OIL FILLED (Oil Circuit Breaker)



Rating in K. V.	Height above Under Side of Support	Bottom to Under Side of Support	Diameter of Bolt Circle to Tank	Diameter over Bolt Lugs	Under Side of Support to Oil Level	Diameter of Clamping Ring	Diameter of Bottom End	Diameter of Top Washer	Number and Size of Bolts to Tank	Overall Length	Number of Petticoats	Top Porcelain	Bottom Porcelain	Inside Diameter of Sleeve	Diameter of Opening in Cover	Metal to Metal Top Porcelain	Metal to Metal Bottom Porcelain	Top of Porcelain to Top of Blade	Capacity in Amperes	Diameter of Center Conductor	Approximate Weight Filled	Approximate Capacity in Gallons	Test Voltage Free in K.V.
	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	*L*	*M*	*N*	*O*	*P*	*Q*	*R*					
	Ft. In.	Ft. In.	Ft. In.	Ft. In.	Ft. In.	Ft. In.	In.	In.	In.	Ft. In.		Ft. In.	Ft. In.	In.	Ft. In.	Ft. In.	Ft. In.	Ft. In.	Lb.	In.	Lb.		
88	4 $4\frac{3}{4}$	3 $4\frac{3}{16}$	$16\frac{3}{8}$	$18\frac{1}{8}$	$19\frac{11}{16}$	$12\frac{3}{8}$	$8\frac{3}{4}$	$8\frac{5}{8}$	$6\frac{3}{4}$	7 $8\frac{15}{16}$	8	2 $9\frac{1}{2}$	19	$7\frac{5}{8}$	$13\frac{1}{4}$	2 4	$13\frac{1}{2}$	$17\frac{13}{16}$	800	$1\frac{3}{4}$	500	9.1	300
88A	4 $11\frac{1}{2}$	3 $4\frac{3}{16}$	$16\frac{3}{8}$	$18\frac{1}{8}$	$19\frac{11}{16}$	$12\frac{3}{8}$	$8\frac{3}{4}$	$6\frac{1}{8}$	$6\frac{3}{4}$	8 $3\frac{11}{16}$	10	3 $4\frac{1}{4}$	19	$7\frac{5}{8}$	$13\frac{1}{4}$	2 $10\frac{3}{4}$	2 $13\frac{1}{2}$	$17\frac{13}{16}$	800	$1\frac{3}{4}$	550	9.5	250
110	5 $\frac{3}{4}$	3 $8\frac{11}{16}$	$18\frac{7}{8}$	$20\frac{5}{8}$	$19\frac{11}{16}$	$14\frac{1}{2}$	$8\frac{3}{4}$	$10\frac{3}{4}$	$9\frac{3}{4}$	8 $9\frac{7}{16}$	9	3 $5\frac{1}{2}$	24	$9\frac{5}{8}$	$15\frac{3}{4}$	2 11	$17\frac{1}{2}$	$17\frac{13}{16}$	800	$1\frac{3}{4}$	730	17.4	300
110A	5 $8\frac{1}{4}$	3 $8\frac{11}{16}$	$18\frac{7}{8}$	$20\frac{5}{8}$	$19\frac{11}{16}$	$14\frac{1}{2}$	$8\frac{3}{4}$	$10\frac{3}{4}$	$9\frac{3}{4}$	9 $4\frac{15}{16}$	11	4 1	24	$9\frac{5}{8}$	$15\frac{3}{4}$	3 $6\frac{1}{2}$	$17\frac{1}{2}$	$17\frac{13}{16}$	800	$1\frac{3}{4}$	730	17.4	300
132	5 $8\frac{1}{4}$	4 $\frac{3}{16}$	$20\frac{3}{4}$	$22\frac{1}{2}$	$19\frac{11}{16}$	17	$8\frac{3}{4}$	$10\frac{3}{4}$	$9\frac{3}{4}$	9 $8\frac{7}{16}$	10	3 $11\frac{1}{2}$	2 $3\frac{1}{2}$	$11\frac{5}{8}$	$17\frac{5}{8}$	3 5	21	$19\frac{13}{16}$	800	$1\frac{3}{4}$	780	18.1	300
132A	6 $4\frac{1}{4}$	4 $\frac{3}{16}$	$20\frac{3}{4}$	$22\frac{1}{2}$	$19\frac{11}{16}$	17	$8\frac{3}{4}$	$10\frac{3}{4}$	$9\frac{3}{4}$	10 $4\frac{7}{16}$	12	4 $7\frac{1}{2}$	2 $3\frac{1}{2}$	$11\frac{5}{8}$	$17\frac{5}{8}$	4 1	21	$19\frac{13}{16}$	800	$1\frac{3}{4}$	1010	26.5	350
154	6 $2\frac{3}{4}$	4 $3\frac{11}{16}$	$22\frac{7}{8}$	2 $\frac{5}{8}$	$19\frac{11}{16}$	$19\frac{1}{8}$	$8\frac{3}{4}$	$10\frac{3}{4}$	$9\frac{3}{4}$	10 $6\frac{7}{16}$	11	4 6	2 7	$13\frac{1}{2}$	$19\frac{3}{4}$	3 $1\frac{1}{2}$	2 $\frac{1}{2}$	$19\frac{13}{16}$	800	$1\frac{3}{4}$	1060	27.5	350
154A	6 $11\frac{1}{4}$	4 $3\frac{11}{16}$	$22\frac{7}{8}$	2 $\frac{5}{8}$	$19\frac{11}{16}$	$19\frac{1}{8}$	$8\frac{3}{4}$	$10\frac{3}{4}$	$9\frac{3}{4}$	11 $8\frac{15}{16}$	13	5 $2\frac{1}{2}$	2 7	$13\frac{1}{2}$	$19\frac{3}{4}$	4 8	2 $\frac{1}{2}$	$19\frac{13}{16}$	800	$1\frac{3}{4}$	1290	42.2	400
165	6 $9\frac{7}{8}$	5 $\frac{3}{16}$	2 $1\frac{1}{2}$	2 $3\frac{1}{4}$	2 $\frac{11}{16}$	$21\frac{1}{8}$	$8\frac{5}{8}$	$13\frac{1}{2}$	$12\frac{3}{4}$	11 $10\frac{1}{16}$	13	5 $\frac{1}{2}$	2 $10\frac{1}{2}$	$15\frac{1}{2}$	$22\frac{3}{8}$	4 6	2 4	$20\frac{7}{16}$	800	$1\frac{3}{4}$	1350	43.2	400
187	7 $6\frac{1}{8}$	5 $7\frac{5}{16}$	2 $4\frac{1}{2}$	2 $6\frac{1}{4}$	2 $4\frac{11}{16}$	2 $\frac{1}{4}$	$14\frac{3}{4}$	$13\frac{1}{2}$	$12\frac{3}{4}$	13 $1\frac{7}{16}$	14	6 $6\frac{3}{4}$	3 $1\frac{1}{2}$	$17\frac{1}{2}$	2 $1\frac{1}{2}$	5 $\frac{1}{4}$	2 7	$20\frac{7}{16}$	800	$1\frac{3}{4}$	1850	60	450
220	9 $1\frac{9}{16}$	5 $11\frac{13}{16}$	2 8	2 10	2 $4\frac{11}{16}$	2 3	$14\frac{3}{4}$	$13\frac{1}{2}$	$12\frac{3}{4}$	15 $1\frac{3}{8}$	16	7 $\frac{1}{16}$	3 6	20	2 $4\frac{7}{8}$	6	2 $11\frac{1}{2}$	2 $\frac{7}{16}$	800	$1\frac{3}{4}$	3260	105	565

NOTE:—"A" bushings are for use at elevations in excess of 4000 ft. above sea level.

FIG. 82.—Locke oil-filled bushing.

Ohio Brass Company bushings, in general, have a wider variation between wet and dry flashover than the Westinghouse and General Electric types previously described. On the other hand, they are practically proof against failure by puncturing. The large diameter of these bushings makes

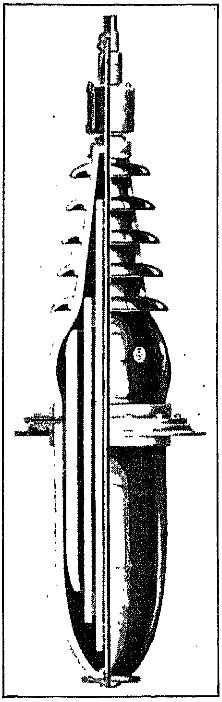


FIG. 83.—Ohio Brass Company oil-filled bushing.

FIG. 84.—Brown Boveri oil-filled bushing, European type.

for very poor bushing type current transformer characteristics.

The Brown Boveri bushing shown in Fig. 84 is of the same general construction as the Ohio Brass Company bushings but is much smaller in diameter in proportion to its length and is not fitted with the internal shield found in the Ohio Brass bushings. The bushings supplied with the orig-

inal Brown Boveri oil circuit breaker installations in the United States were made in Europe, but at the present time they are made in America to Brown Boveri specification.

The porcelain-insulated oil-filled bushings are subject to the same requirements for oil tightness and must be handled with the same care as the herkolite-insulated bushings of the General Electric Company. *One factor is important and requires careful attention in connection with all oil-filled bushings, and that is the precaution to insure that the bushing is thoroughly dry before filling with oil.* Much trouble ascribed to faulty design of oil-filled bushings has been due to the presence of water inside the bushing.

GENERAL

From the standpoint of the operating engineer, the oil circuit breaker bushing should

1. Flashover before puncture.
2. Flashover outside the oil circuit-breaker tank before it does inside.
3. Be rated in place in the breaker.

The operator can then determine the necessary values needed for safety in a given location. There is an increasing tendency on the part of operating engineers to fit the insulation to the duty which it will be called upon to handle in service. Some power companies operating large networks have divided their systems up into insulation districts based upon climatic and other conditions and have assigned definite and different insulation requirements to each district. There are two major considerations entering into the determination of these insulator requirements, and they are

1. Leakage.
2. Impact.

Leakage is the controlling factor in districts subject to salt fogs or sprays such as are to be found along the coast lines. It is, also, the controlling factor in those districts

where a long, dusty, dry season may be followed by gentle rains which do not wash the insulators thoroughly.

Impact is the controlling feature in those districts where lightning is prevalent. The method of rating oil circuit-breaker bushings has not as yet been standardized to the extent that the prospective user can determine definitely what to purchase, even if he knew definitely what his operating conditions were. Frequently, these conditions, also, are in doubt.

Flashover tests at normal frequency should, from an operating standpoint, be made with the assembled breaker, though this complicates the manufacture somewhat.

The customary procedure, however, is to test the bushing alone and determine its rating and then to give the assembled breaker the A. I. E. E. tests (see p. 100) on which to base the oil circuit-breaker rating.

Specifications, from both the manufacturer and the purchaser, usually call for the following test data on bushings:

1. Dry flashover at operating frequency.
2. Wet flashover at operating frequency.
3. Dry test, assembled in oil circuit breaker, A. I. E. E. standards $2\frac{1}{4}$ times nominal operating voltages plus 2,000 for 60 sec. (see p. 100).
4. Impulse-ratio or impact-flashover voltage.
5. Current-carrying capacity of conducting parts.

Definite specifications on 1, 2, 3, and 5 are available in the A. I. E. E. standards. Impact-flashover voltage determination is not yet standardized to the point where the various types of insulators may be compared, unless tested by the same equipment. The impulse ratio is defined as the ratio of the impulse-voltage flashover to the normal-frequency flashover value and is in itself not specific unless the characteristics of the wave are given.

The original work by Peek on the impulse generator (49) defined the rise and decay of the wave of voltage, since

flashover could occur after the peak of the impulse wave if such a wave were fast enough.

Quoting a later discussion by Mr. Peek (50):

> The early work with this lightning generator showed that the impulse-sparkover or breakdown voltage was always higher than the 60-cycle or continuously applied breakdown voltage due to time lag. The ratio between the impulse-breakdown voltage and the 60-cycle voltage was called the "impulse ratio." This term is still used to indicate the relative values of insulation for lightning or impulse breakdown. The higher this ratio under given conditions the greater the lag. This research showed that for electrodes giving an approximately uniform field, as, for instance, the sphere gap, the lag was small or the impulse ratio was approximately unity over a large range of impulses. It also showed that for irregular fields the lag was appreciable and the impulse ratio increased with the steepness of the wave front. In other words, it was found that the lag was not constant but varied with the duration or rate of application of the voltage as well as with the type of electrode used. Since the impulse ratio of the sphere gap approximated unity except for the very steepest waves, it offered a means of measuring transient voltages and has been an almost indispensable tool in such investigations.

The actual air breakdown as visualized by one engineer, C. L. Fortescue (51), is as follows:

> The stages of breakdown are
>
> 1. Free electrons drawn into the field.
>
> 2. Free electrons are increased by ionization by collision, recombination taking place, also.
>
> 3. A critical stage is reached where the rate of ionization and volume density of the free electrons have reached a critical point, which shows itself in the emission of ultraviolet rays. This results in the final stage, where it is believed that molecular disassociation of the air molecules takes place, which is shown by intense white streamers which form at the electrode having the greatest intensity, and these streamers grow outward from the electrode and, finally, grow together and cause breakdown.
>
> The growth of these streamers takes place progressively from the electrode outward, and it apparently has a velocity of propagation which is proportionate to the difference of potential between the electrodes, so that, from this point on, the breakdown takes

place as a function of time. It is not instantaneous but takes an appreciable time.

This is the factor which is responsible for the fact that with very steep wave fronts an insulator, or a string of insulators, has what is known as an "impulse factor." That is to say, it breaks down at a higher value than the normal 60-cycle flashover. . . .

Breaking down is not an instantaneous process; it takes time. So during the time that the breakdown is taking place the voltage is still rising, and the actual arcover will take place at some higher voltage the magnitude of which will depend upon the character of the insulator or spark gap. Now, if we were to have a wave which just reached the 60-cycle flashover, or critical point, and then remained at that voltage for an appreciable length of time, and then came down, the flashover would take place at some appreciable time from the point at which it reached that voltage, and the potential recorded would be the same as the 60-cycle flashover potential or slightly higher. If, however, the same wave had been still going up, the voltage recorded would not be the 60-cycle voltage, but the flashover would take place at some time after this stage had been reached and at a higher value. This time can be calculated by the velocity at which these streamers come together.

The steeper the wave front the higher the voltage that will be reached before those streamers come together. But the velocity increases with the potential, and the actual time that elapses between the critical point and the point of flashover becomes somewhat less as the steepness increases, so that we can figure out the points for each steepness.

Work by A. O. Austin, of the Ohio Brass Company, indicates that once the actual flashover starts, the action is extremely fast in some cases, too fast to be clearly recorded by the usual Dufour oscillograph. According to him, the process can be followed step by step until the field is built up and the streamers are drawn together, but from this point the breakdown is very fast.

Applications of the studies now going on have not been made on the practical apparatus, nor has a uniform method of test been developed for field or factory determination of impulse ratio on breaker bushings. A. I. E. E. committees are now (1929) working on such rules.

One other point in this connection, important from the

operator's standpoint, is that the impulse value is practically independent of weather conditions (52).

Quoting from the A. I. E. E. discussion:

> The voltage required to produce flashover under these conditions (impulse-wet flashover test) was approximately the same on the average as required when the bushing was dry. This fact is of special importance in a discussion of the performance of bushings under service conditions. It demonstrates that the wet-flashover voltage of a bushing is of interest only in terms of the system frequency. If the wet flashover is of such value that it exceeds any low-frequency potential that can occur on the system, there is nothing gained by increasing it further. Since voltages of the order of magnitude of flashover of bushings of good design occur in service only under impulse conditions where the wet and dry flashover voltages are the same, it becomes of prime importance to relate properly the impulse flashover of the bushing to other insulations on the system and particularly to the puncture strength of the bushing itself under impulses. Beyond question, a bushing should be self-protecting under impulse voltages as well as at normal frequency, so that it may withstand impulse flashover without puncture in service.

The original paper by Peek gives values for impulse flashover of suspension strings, wet and dry, substantiating the above analysis (53). In connection with impulse-flashover values, it is to be remembered that if the oil and the air are stressed to equal values, the end of the bushing in air will flashover first, due to the time lag of the oil.

At the present time, the several manufacturing companies use different impulse-wave characteristics, which are changing as new knowledge becomes available. The general statement may be made, however, that unless the impulse values given are accompanied by a definite statement as to the shape of the wave as to both rate of growth and decay, the only safe method is to make sure that flashover occurs on the building-up portion. This results in what is termed a "chopped wave," since when flashover occurs the voltage across the bushing drops to the value across the power arc, usually only a very small part of that required for flashover.

There are, in general, two types of impulse generators in common use: first, that used by Steinmetz and described by Peek, as shown diagrammatically in Fig. 85 in A and broken down to show the essential circuit in C of the same figure.

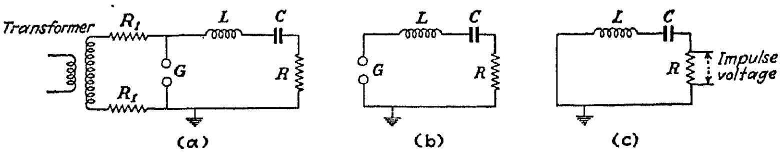


FIG. 85.—General Electric impulse-generator diagram.

The fundamental equations, according to Peek, are

Equations for Calculating Impulse Generator Waves.
Trigonometric (Oscillatory) Case: Maximum voltage:

$$e_{\text{max.}} = \frac{2ER}{q}\epsilon^{-\frac{R}{q}\tan^{-1}\frac{q}{R}} \sin \tan^{-1}\frac{q}{R}.$$

Where $e_{\text{max.}}$ = the maximum of the impulse voltage;
E = the maximum of the 60-cycle voltage across the gap G (or the condensers at $t = 0$);
R = the resistance of the water tubes;

$$q = \sqrt{\frac{4L}{C} - R^2};$$

$$\epsilon = 2.718.$$

Time to reach a maximum:

$$t = \frac{2L}{q}\tan^{-1}\frac{q}{R}.$$

Voltage at any time t:

$$e = \frac{2E}{\sqrt{\frac{4A}{B^2} = 1}}\epsilon^{-\frac{Bt}{2A}} \sin \frac{Bt}{2A}\sqrt{\frac{4A}{B^1} - 1},$$

where $A = C \times L$;
$B = C \times R$;
$\epsilon = 2.718$.
C expressed in farads. R expressed in ohms.
L expressed in henrys. t expressed in seconds.

Logarithmic (Impulse) Case: Maximum voltage:

$$e_{\text{max.}} = \frac{ER}{S}\left[\left(\frac{R+S}{R-S}\right)^{-\frac{R-S}{2S}} - \left(\frac{R+S}{R-S}\right)^{-\frac{R+S}{2S}}\right],$$

where $e_{\text{max.}}$ = the maximum of the impulse voltage;
E = the maximum of the 60-cycle voltage across the gap G (or the condensers at $t = 0$);
R = the resistance of the water tubes;

$$S = \sqrt{R^2 - \frac{4L}{C}}.$$

Time to reach a maximum:

$$t = \frac{L}{S}\log_\epsilon\left(\frac{R+S}{R-S}\right).$$

Voltage at any time t:

$$e = \frac{E}{\sqrt{1 - \frac{4A}{B^2}}}\left[\epsilon^{-\frac{Bt}{2A}\left(1-\sqrt{1-\frac{4A}{B^2}}\right)} - \epsilon^{-\frac{Bt}{2A}\left(1+\sqrt{1-\frac{4A}{B^2}}\right)}\right]$$

where $A = C \times L$;
$B = C \times R$;
$\epsilon = 2.718$.
C expressed in farads. R expressed in ohms.
L expressed in henrys. t expressed in seconds.

The capacity of the specimen under test changes the form of the equation from a quadratic to a cubic and physically tends to decrease the steepness of the wave by delaying the maximum.

Below 10 per cent of the capacity of the main condenser, designated as C, there is no essential change in the wave

shape, but for testing oil circuit breaker bushings in place in the breaker, a correction should be made.

The second form, used principally by the Westinghouse Electric and Manufacturing Company, consists of apparatus whereby condensers may be charged in parallel and discharged in series. Figure 86 gives the elementary circuit. This circuit was described by Dr. E. Marx (54) as being used

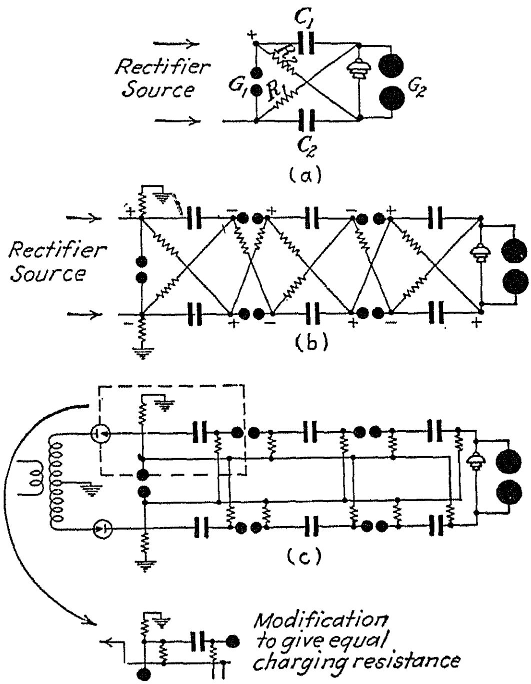


FIG. 86.—Type of impulse generator used by Westinghouse Company.

in European laboratories and with some modifications has been used in this country for voltages as high as 1,000,000 volts (55).

The Ohio Brass Company uses an impulse generator, as shown in Fig. 87, somewhat similar to that used by several high-tension laboratories in the United States. Its mode of action is similar to that used by the General Electric Company.

As stated previously, no specific standards are available for impulse testing, so that the engineer writing specifications for oil circuit breaker bushings must either neglect that phase entirely or so describe the method of test that the requirements are clearly defined. This is, at present, also, difficult to do; consequently, no entirely satisfactory specification is available.

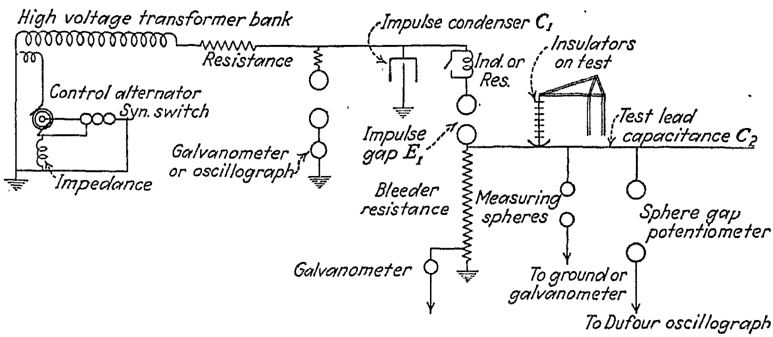


FIG. 87.—Ohio Brass impulse generator.

The method sometimes adopted is to supply a curve of flashover plotted with time against voltage. While cumbersome, this method is accurate and must serve until further knowledge is available.

CHAPTER XVI

ACTUATING OR OPERATING EQUIPMENT

The development of apparatus for the operation of oil circuit breakers followed closely the development of the breakers themselves, and by 1894 there had been produced both pneumatically and motor-operated equipment. Solenoid operators followed a little later. Types of pneumatic and solenoid operators are shown in Figs. 4 and 17, which illustrate the early low-voltage oil circuit breakers. The pneumatic operators never gained the favor accorded the electric operators, due to the necessity for maintaining air compressors and receivers together with their interconnected piping. Very early in the progress of the art, the advantage of the storage battery as a source of energy for oil circuit breaker operation was realized, and batteries are almost universally used at the present time. The simplicity of the solenoid as a means of imparting a linear motion to the operator soon made it the predominating method, and, until quite recently, by far the larger portion of electrically operated breakers were equipped with solenoid mechanisms.

The first high-voltage oil circuit breakers were hand-operated, the actuating equipment consisting of a lever attached directly or through a bell crank and shaft combination to the movable contacts. They were non-automatic in operation and had to be opened by hand. The experience gained with the operators for the lower-voltage breakers was available for application on the problem of actuating the higher-voltage breakers, and by the time satisfactory breakers had been developed and were offered by the manufacturing companies, suitable equipment for their operation was also available.

The requirements for a suitable oil circuit breaker operator have always been primarily the same. The relative importance of these requirements may vary somewhat with breaker location and duty, but, as usually enumerated, they are

1. Reliability.
2. Speed.
3. Mechanical characteristics (trip free, etc.).
4. Energy requirements.
5. Ease of maintenance.

The operators now in use have been gradually developed as experience has pointed out desirable features and improvements, and their evolution has been along lines somewhat as follows:

1. Hand or manually controlled.
2. Pneumatic and hydraulic.
3. Direct-geared motor.
4. Solenoid.
5. Motor-operated centrifugal mechanism.
6. Opposing springs.
7. Separate opening and closing springs.

In the discussion which follows, typical examples of the above types as represented in present-day practice will be noted and their characteristics pointed out in accordance with the table of requirements enumerated above.

Manual Control.

Examples of strictly manually controlled breakers for high-tension work, such as the Stirling breaker shown in Fig. 12, are difficult to find except in relatively old stations still retaining obsolete equipment. The reason is that any station important enough to be a part of a high-voltage system usually has some form of energy available which will permit the use of remote control of the breakers by one or the other of the mechanical devices enumerated. A still more important reason is that modern operating practice

demands relay protection in one form or another on the greater portion of the high-voltage breakers now in use.

In some instances, where single high-voltage oil circuit breakers are installed on isolated transformer banks, they may be arranged for manual closing but are usually equipped with some form of electric tripping device which will open the breaker by relay operation. This tripping device may consist of a very small solenoid actuated by current from a current transformer or by a series coil within the breaker itself and has an energy requirement very much less than that which would be required to close the breaker. Practically all high-tension oil circuit breakers, however, have provision made in their operators for some form of manual control to be used in case of emergency or when making adjustments during maintenance work.

Pneumatic and Hydraulic Operators.

Among the earliest operators developed for high-voltage oil circuit breakers were the pneumatic types shown in Figs. 4 and 20, the latter being the first type of 110-kv. oil circuit breaker built and known as the "type T" breaker. In general, the troubles with the pneumatic operators may be grouped under two of the headings, *i.e.*, reliability and maintenance. The type of control used on the type T breakers had two vital faults. First, it was not positive, and the pistons might stop at any part of the stroke. Frequently, oil would leak back past the piston of the closed breaker, partially filling the cylinder and preventing the switch from completely opening; similarly on closing. Secondly, there was no mechanical interconnection between phases, and it was possible to have only two of the three phases close, or open, as the case might be. There were additional disadvantages, such as excessive and rather difficult maintenance and high cost.

Some modern breakers are equipped with pneumatic operators. One large power company on the Pacific Coast

uses a great many such equipments and has installed them in recently completed new substations. These modern equipments are usually controlled from a single cylinder, which operates all the poles of the breaker through a system of shafts and bell cranks. Air-brake valves and fittings are used in the control piping. The reliability of the power source is probably not so great as in the case of the storage battery, and the equipment is more susceptible to trouble from freezing and the accumulation of dirt. There are, also, certain difficulties in relay protection, because of the fact that all standard relay equipment is designed for electric control.

Hydraulic control has been used, in some instances, where very heavy duty was required, such as high current-carrying capacity breakers in an isolated phase arrangement. This method has not been used for high-voltage oil circuit breakers. The remarks concerning the operation of pneumatically controlled equipment apply, also, to the hydraulic control.

Solenoid Control.

The major portion of high-voltage oil circuit breaker controls, built from 1906 or 1907 to about 1923, may be grouped under the general heading of solenoid controls. This type of control is still popular, and probably one-half of the breakers built since 1923 have been equipped with solenoid operators. They are universally designed for use on direct-current circuits, usually 125 to 250 volts, with a storage battery as the source of power. The solenoids offered by the several manufacturers of oil circuit breakers in themselves do not differ greatly, the usual form being of an iron-clad, short-stroke type. There is, however, a wide variation in the method of attachment to the breaker mechanism.

Typical Westinghouse solenoids are shown in Figs. 88 and 89. They are the type usually supplied with the high-

voltage oil circuit breaker and are of the conventional iron-clad, short-stroke type. These mechanisms are mechanically

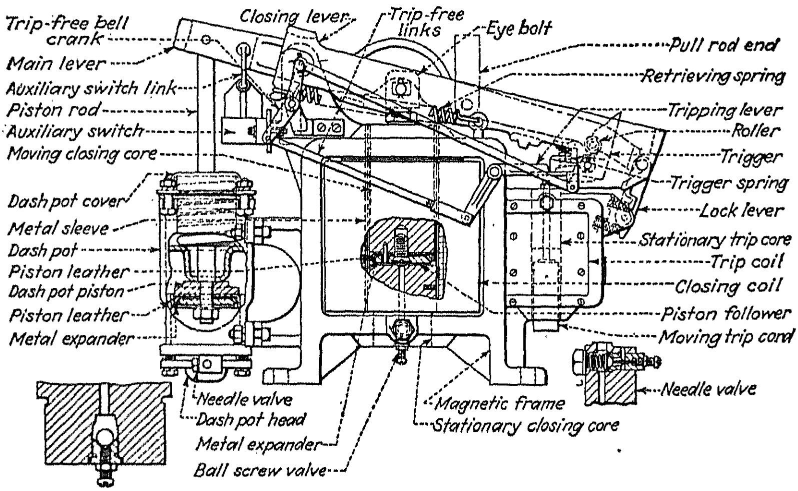


Fig. 88.—Westinghouse solenoid.

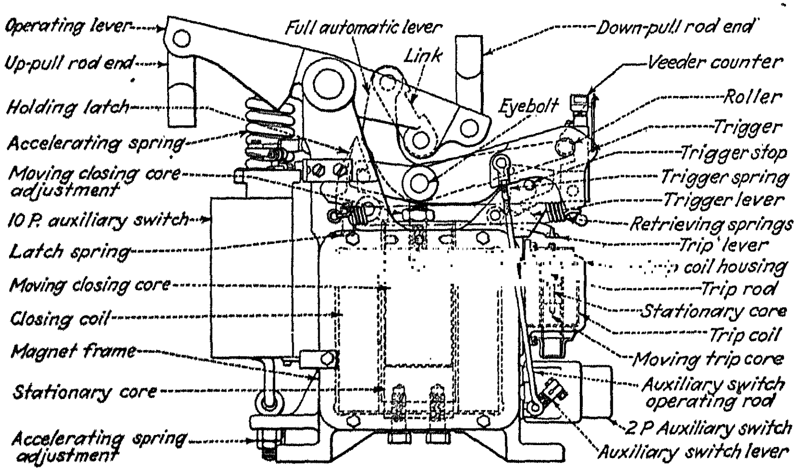


Fig. 89.—Westinghouse solenoid, later type than Fig. 88.

trip free. The solenoid acts to close the breaker against gravity and the compression of a "kick out" or accelerating spring.

The arrangement of springs and bell-crank mechanisms is shown in Fig. 91. The "speed-time" curves for a Westinghouse type G-2, 187,000-volt oil circuit breaker with

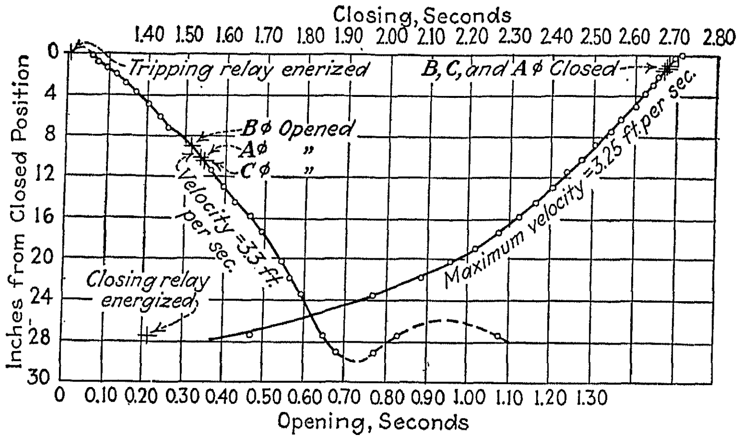


FIG. 90.—Speed-time curve of Westinghouse G-2, 187–220-kv., solenoid-operated oil circuit breaker.

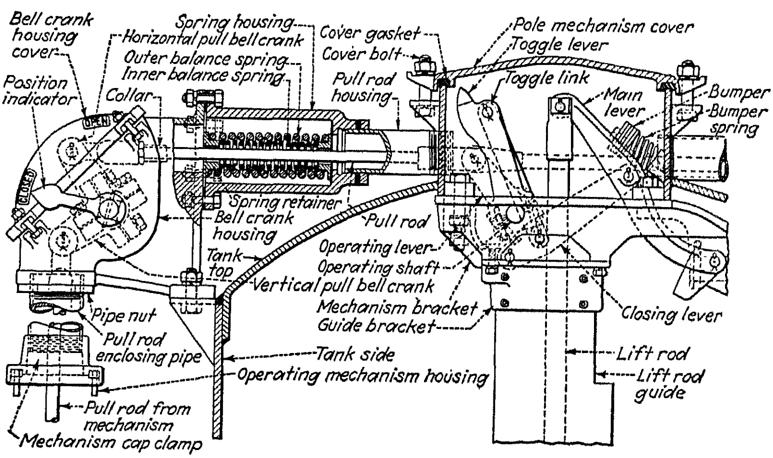


FIG. 91.—Westinghouse operating mechanism for G-22, 154 kv. oil circuit breaker.

solenoid operator are shown in Fig. 90. These curves show graphically the length of time elapsing from the instant the closing or tripping relay is energized until the contacts have

completed their full travel. The position of the contacts at any instant, and the rate of travel, may be noted from the curve.

Due to the inherent characteristics of a solenoid with its core, by virtue of which the pull increases as the core is drawn into the coil, the closing curve indicates a steadily increasing speed as the solenoid core approaches nearer and nearer the end of its stroke. This is an undesirable feature, as the control mechanism must be brought to rest at the end of the stroke, and a decreasing velocity would be preferable to an

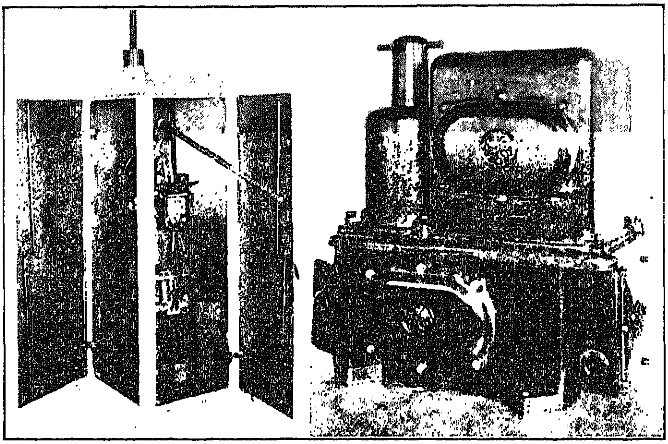


FIG. 92.—General Electric solenoid operator.

increasing one. The different groups of designers have used various devices to mitigate or overcome the shock incidental to stopping the mechanism at the end of its travel. In the case of the Westinghouse operators illustrated, a "bumper spring" will be noted in Fig. 91 and two dashpots in Fig. 88. One of the dashpots is formed by the solenoid and core acting as cylinder and piston, and the other is mounted outside the solenoid and attached directly to the operating lever. The Westinghouse solenoid mechanisms of the most recent design, as shown in Fig. 89, are mechanically trip free from any position of the stroke and have no dash-

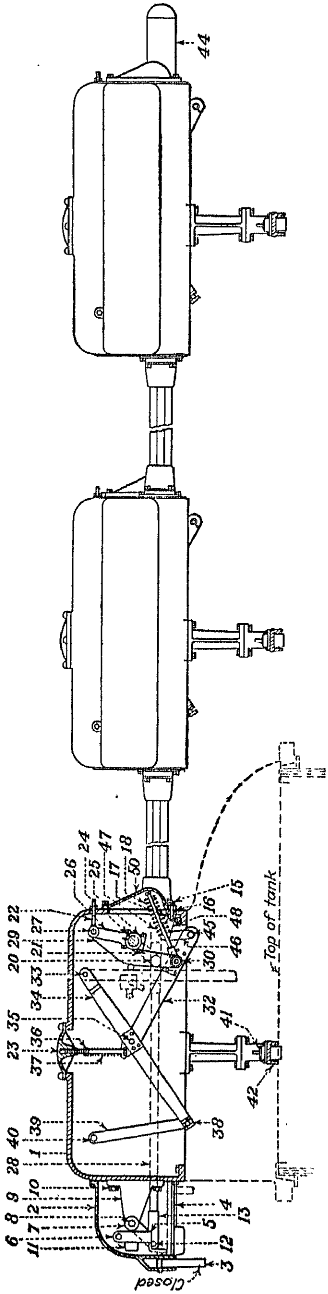


Fig. 93.—General Electric operating mechanism.

pots. The function usually performed of such dashpots is performed partly by the arrangement of levers and in opening by the use of a hydraulic bumper which acts under oil for the last few degrees of the stroke. No speed curves are available for the new line of breakers at the present time.

In general, only typical types can be considered, since various combinations may be found on a given type of breaker, depending upon the year of manufacture. Detailed instructions are furnished by the manufacturer with each breaker, as a guide to installation and operation, and maintenance work must be done by an experienced mechanic who at least understands the working principle of the entire mechanism.

The General Electric solenoid mechanisms are somewhat similar to the Westinghouse operators just described, except that, as in the case of the new Westinghouse operator, the damping action is accomplished more by the position of the links and damping springs than by any dashpot effect. One

of the General Electric solenoids is illustrated in Fig. 92, and the lever-and-spring arrangement in Fig. 93. The speed-time curve for a type FKO–36, 115,000-volt breaker is shown in Fig. 94 and is similar in general characteristics to the curve for the Westinghouse breaker.

Those high-tension breakers which do not make use of the action of gravity in opening require a different type of

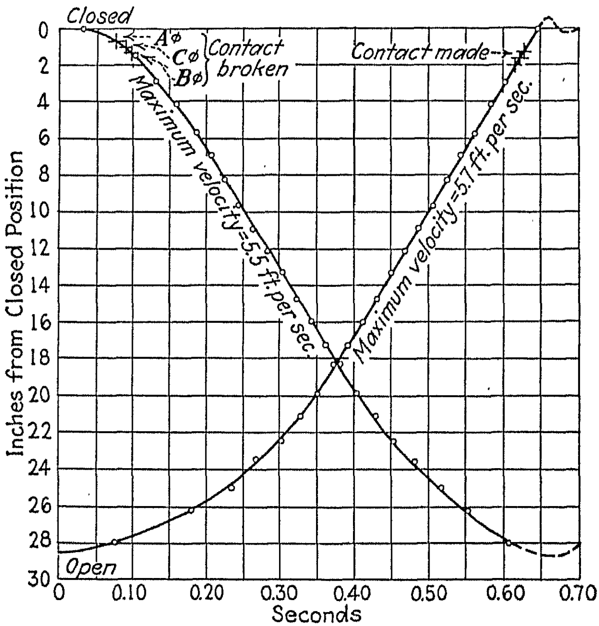


FIG. 94.—Speed-time curve on FKO–36, 33–C, 115-kv. solenoid-operated General Electric breaker.

solenoid mechanism. The Pacific Electric Manufacturing Corp. breakers fall in this class. In these breakers, the blades rotate in a horizontal plane, and it is essential that some initial spring tension be present even in the open position of the breaker. A dashpot is used to check the speed on the opening stroke of this type of solenoid operator, while the energy of the closing stroke is absorbed in springs and dashpots built into the breaker tank. Figure 95 illustrates a typical Pacific Electric solenoid. Figure 96 shows

the speed-time curve of a 110,000-volt breaker. The characteristics of this curve differ somewhat from the General Electric and Westinghouse curves previously shown, due to the action of the accelerating springs on the closing stroke, which assist the solenoid in absorbing velocity to the mechanism during the time of least pull by the solenoid core.

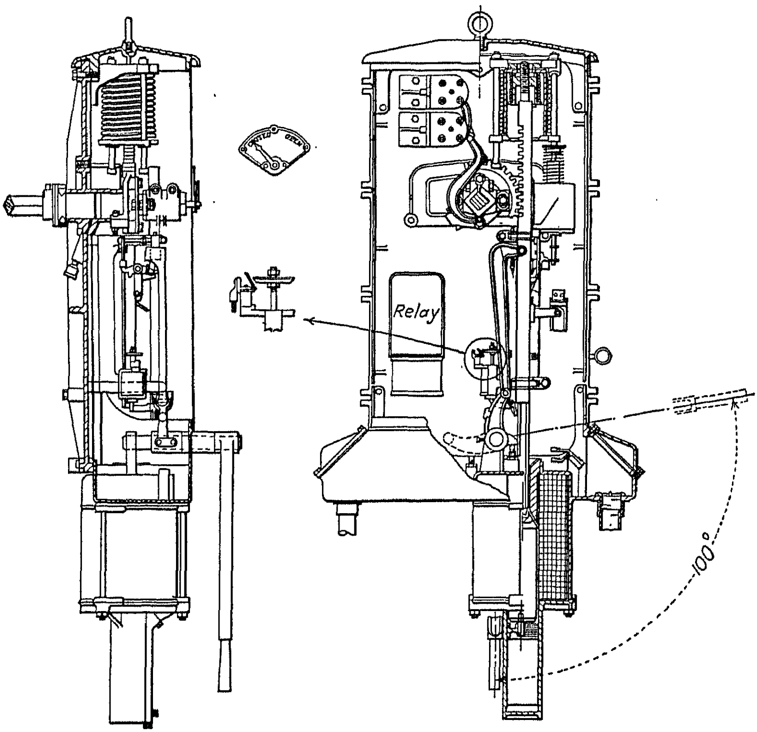


FIG. 95.—Pacific Electric solenoid control.

This type of solenoid is equipped with an auxiliary hand-closing lever, which operates through a ratchet device to control the speed of hand closing in order to prevent slow operation in case of closure into a severe short circuit.

Another type of oil circuit breaker which does not depend upon gravity for its operation is built by the Kelman Electric and Manufacturing Company. In this breaker the

contact motion is linear in a horizontal plane. It is more fully described under the part devoted to modern breakers. A Kelman operator is illustrated in Fig. 97.

Various devices have been used to modify the undesirable closing characteristics of the solenoid, ranging from different lever combinations, of which the Kelman control is an example, to variable-ratio gears and cams. The great

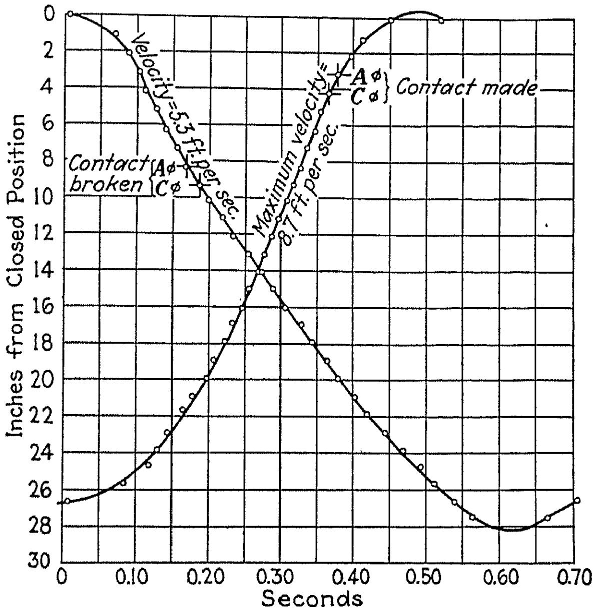


FIG. 96.—Speed-time curve on Pacific Electric six-break, 110-kv. breaker.

variety in the devices used testifies to the thought and study which have been given to the design of solenoid-control mechanisms. The simplicity of the solenoid itself makes it an attractive agent for the operator of oil circuit breakers, and this fact has more than offset its undesirable features until quite recently in the major number of oil circuit breaker applications. The operation of these breakers in service indicates that reasonable performance can be expected from solenoid-controlled breakers.

Several general and common characteristics apply to all types of solenoid operators, and they may be listed somewhat as follows:

1. Due to the fact that a spring is used to impart initial contact speed on opening, it is essential on closing heavy-duty breakers that the latching-in and shock-absorbing devices function perfectly; otherwise, there is a reduction in speed when speed is most needed.
2. In spite of all dashpot or bumper action, there is considerable mechanical shock on closing.

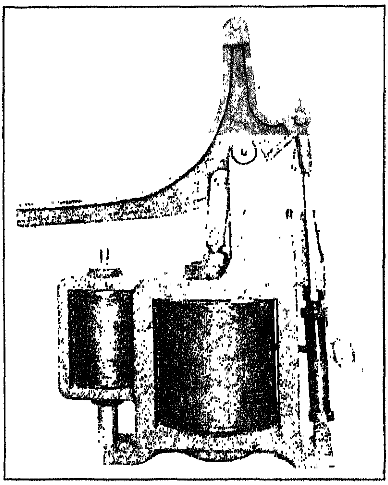


FIG. 97.—Kelman solenoid control.

3. The energy available for final closure is usually reduced to stored energy in the moving parts acting against either springs or dashpots.
4. The energy requirements are high compared to other forms.
5. It is not practicable to use more energy than is actually needed to close the breaker; *i.e.*, the safety factor is low.

The essential features to be observed from the standpoint of the operating man are that the solenoid has sufficient energy to close the breaker and that the mechanism is trip free in action and not unduly hard to adjust and maintain.

Direct-geared Motor Operators.

The direct-geared motor operator has not found general favor in the United States, and the development of this type of operator has been carried on principally in Europe. When the Brown Boveri Company entered the American field,

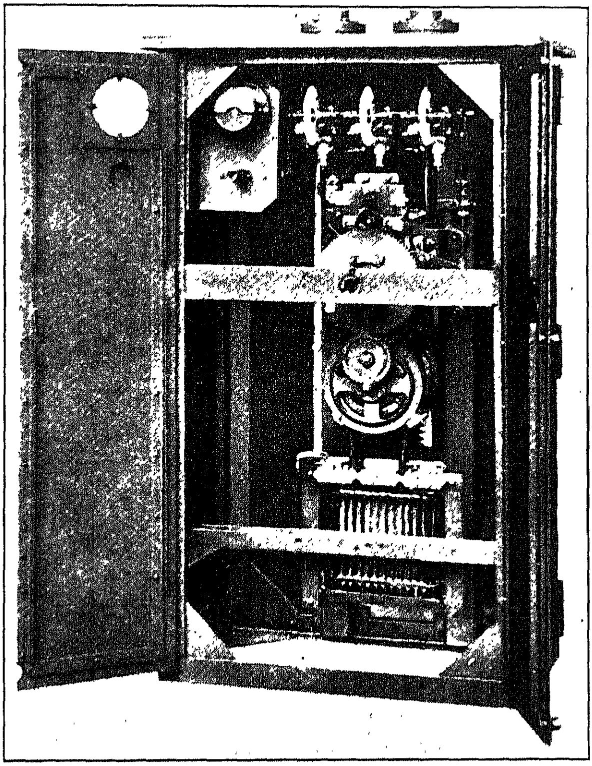


FIG. 98.—Brown Boveri direct-geared motor operator.

the operators developed in Europe made their appearance in connection with the Brown Boveri breakers and are now the best known example of the direct motor-geared type of operator to be found in America.

The operator for a 150,000-volt Brown Boveri breaker is shown in Fig. 98. In this operator, the actuating member is a high-speed motor geared through an overrunning clutch

to the movable contacts of the breaker. The Brown Boveri breakers are of the multiple-break type. The speed of contact travel on both opening and closing is very much less than on the American-designed two-break breakers, being usually less than 2½ ft. per second, as contrasted to speeds of 5½ ft. or more per second. A speed-time curve for a 150,000-volt Brown Boveri breaker is shown in Fig. 99. In this case, the data for plotting the curve were obtained from published test data and were not taken with a position indicator. It lacks the accuracy of the previous speed-time

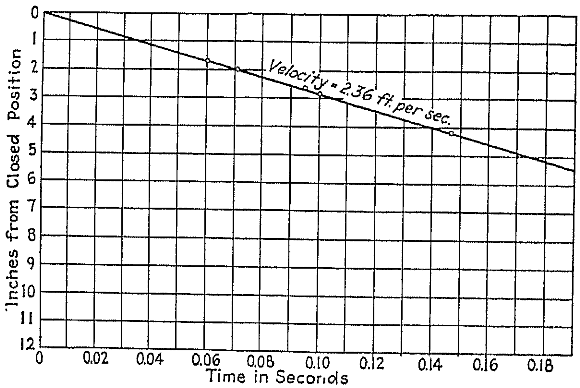


FIG. 99.—Speed-time curve for Brown Boveri AF-2411, 154-kv. breaker (calculated).

curves but is indicative of the characteristics of the operator (56).

Several other types of mechanism of European manufacture may be considered under this same general classification, such as the cam-operated mechanisms, supplied by Oerlikon and others, and the weight-operated types, as furnished by Delle. A Delle breaker is illustrated in Fig. 70. Details of these operators will not be described here, as they have not been used by the American power companies and, in general, lack the operating characteristics demanded by American users.

The difficulties encountered by this class of operator are largely mechanical and hinge principally upon reliability

and maintenance. They have, in common with most of the older solenoid operators, the feature of requiring complete closure of the breaker in order to secure the "kick-out" feature of the accelerating springs for proper opening speeds.

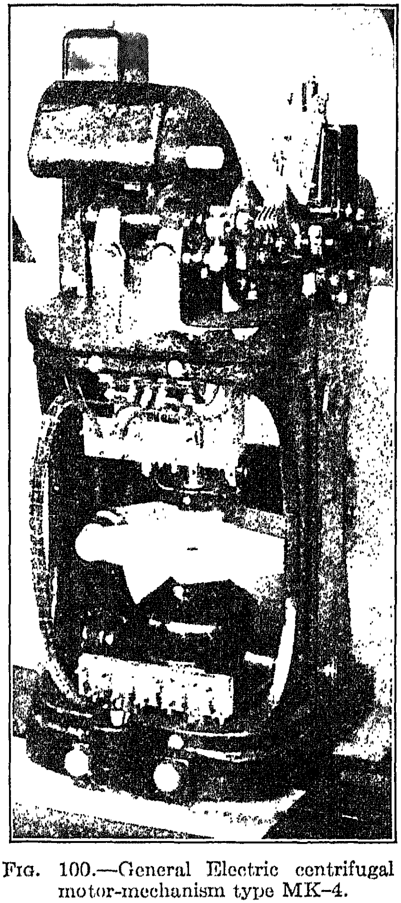


FIG. 100.—General Electric centrifugal motor-mechanism type MK-4.

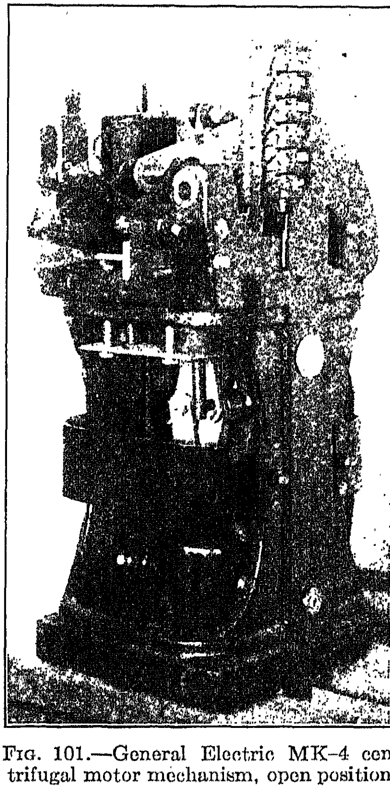


FIG. 101.—General Electric MK-4 centrifugal motor mechanism, open position.

This point has received considerable attention in Europe, and at least one proposal has been made to require complete mechanical closure of the breaker before the tripping action can be started (57). This is, of course, in direct opposition to the demands of American operators, which require a mechanism to be trip free from any position of the closing stroke.

Centrifugal Motor Mechanisms.

Within the past five or six years, the centrifugal type of motor-operated oil circuit-breaker closing mechanism has found favor with American users, and it now shares in popularity with the solenoid type of operator. Its use is becoming more general each year, and at least one large manufacturer has standardized on the centrifugal motor operator for high-voltage oil circuit breakers, listing the

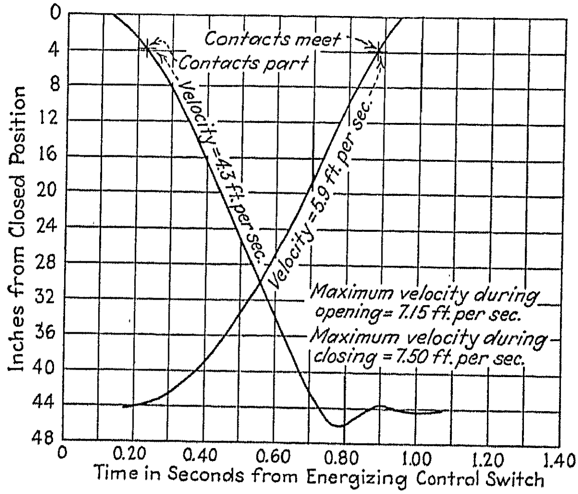


FIG. 102.—Speed-time curve of General Electric 220-kv. breaker with MK-4 operating mechanism.

solenoid operator as special equipment. An example of the General Electric type of operator known as "MK-4" is shown in Figs. 100 and 101. A speed-time curve for a General Electric 220,000-volt type FHKO-39 oil circuit breaker equipped with such an operator is shown in Fig. 102. A Westinghouse type CF-2 motor mechanism is shown in Fig. 103.

The motor is usually of the series or universal type and varies in capacity from ½ to 2 hp., depending upon the size of the breaker and the duty required. It may be either an alternating- or a direct-current motor, although the latter

is preferred as it permits the use of storage battery for the supply of energy which will be available, regardless of the condition of the supply of alternating current to the station buses.

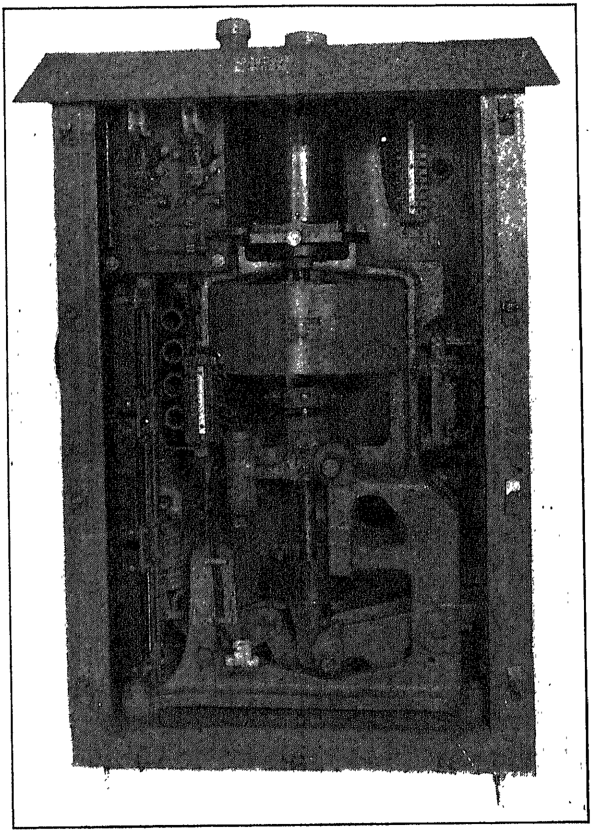


FIG. 103.—Westinghouse centrifugal motor mechanism.

The closing characteristics are somewhat better than that of the solenoid-operated mechanisms, and the current drain on the storage battery not so great. The current inrush at starting is only slightly less than the current requirements of an equivalent solenoid mechanism, but it drops rapidly as the motor gains speed. The sustained cur-

rent for the operator of a 110,000-volt breaker is well over 100 amp. at 125 volts, and heavy-duty control leads are required to maintain a sufficiently high voltage at the terminals of outdoor mechanisms located at any considerable distance from the storage battery.

The centrifugal motor mechanisms have, in most cases, proved superior to the solenoid operators for equipment duties. Such troubles as have developed have been principally due to maladjustment or mechanical difficulties, such as lack of lubrication. On some of the older types of centrifugal mechanisms, operation was greatly slowed up, due to the necessity for allowing flyballs to come to rest before a second closure could be made after trip-out. This required half a minute or more, and if care was not exercised in the operation of the equipment, it was possible to lock the operator by attempting to reclose the breaker before the mechanism had come to rest. This difficulty has now been overcome, and the mechanisms are trip free from any position of the stroke and reasonably fast in operation. No data on the torque developed are available.

Opposing-spring Operators.

The idea of storing energy in springs for oil circuit breaker operation is very old, and one of the earliest applications is seen in the General Electric type H breaker illustrated in Fig. 5. In this case, both the opening and closing strokes of the breaker are started by the springs, which impart a very fast start to the contacts and permit the motor to come up to speed and complete the stroke, after which they are rewound, ready for the next operation in the opposite direction. This principle is still in use on the General Electric type H breakers for use at 15,000 volts and less.

The operators furnished by the German firm of Voigt and Haeffner are of the opposing-spring type and are illustrated in Fig. 104, which shows the general appearance of

the equipment, and Fig. 105, which shows schematically the method of operation. American examples of this type of operator are shown in the Condit operator (Fig. 106) and the Kelman operator (Fig. 107). All mechanisms of this type close the breaker against the action of an accelerating or "kick-out" spring and must be sufficiently strong to accomplish this purpose and insure positive closure. The difficulties in obtaining trip-free action are the same as in the case of the solenoid and direct-motor drive mechanisms. This class of operator has not been extensively used on high-voltage oil circuit breakers.

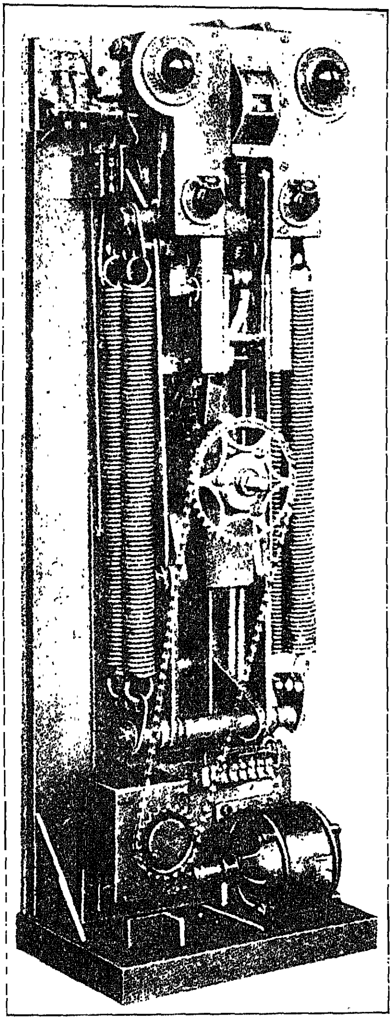


FIG. 104.—Voigt and Haeffner operating mechanism.

Separate Spring Operators.

The action of a stressed spring is exactly opposite to that of a solenoid with its core, in that the spring exerts its maximum effort at the instant of release and gradually loses force as it nears the end of its stroke. In the solenoid, the force increases as the core is pulled into the solenoid coil until the maximum pull is exerted when the core is centrally located within the coil. The spring, therefore, offers some

advantages for use in imparting motion to an oil circuit breaker operator, for it exerts its maximum pull on the instant of release and can, therefore, quickly accelerate the moving elements of the breaker. When properly designed, it will have expended most of its stored energy when the contacts are fully closed, automatically cushioning the

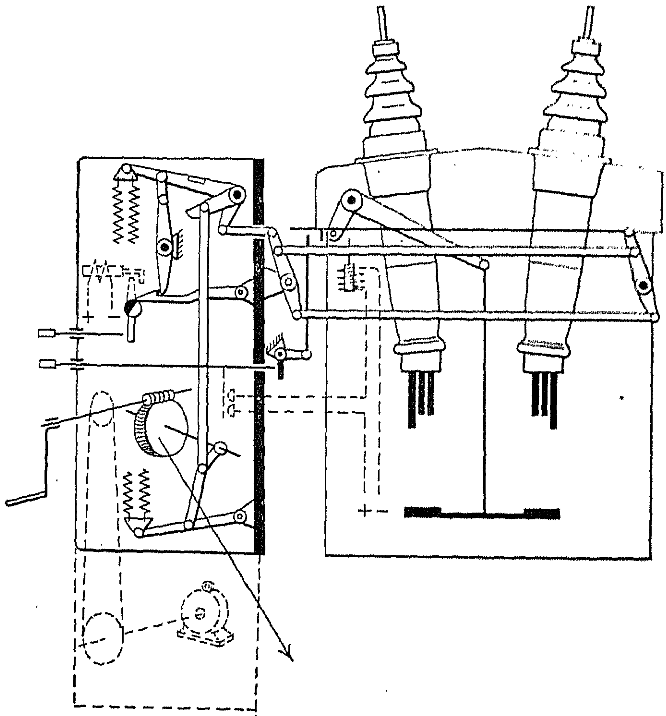


Fig. 105.—Schematic diagram of Voigt and Haeffner mechanism.

mechanism and lessening the mechanical shock which accompanies the stopping of a rapidly accelerating mechanism.

One of the newer types of oil circuit breaker operating mechanisms makes use of separate springs for opening and closing the breaker. The springs are compressed simultaneously by a small motor, each being locked in position by a toggle. The details of this operator, which is the

product of the Pacific Electric Manufacturing Corporation, are shown in Fig. 108, while a schematic diagram of the method of operation is shown in Fig. 109.

In this operator, the energy is stored in both the closing and opening springs before any operation of the circuit breaker is started. The breaker may then be closed by

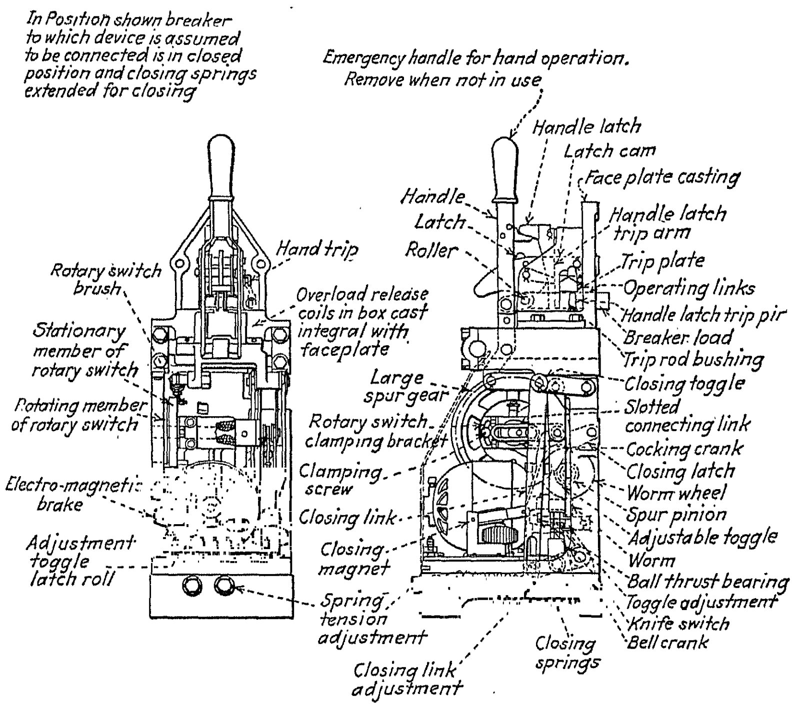


FIG. 106.—Condit motor mechanism.

releasing the closing spring, which remains extended until after the opening spring is tripped, at which time both springs are again compressed by the motor. The springs are wholly independent of each other and may be designed to deliver any desired energy on either the closing or the opening stroke. The mechanism is entirely trip free, for the release of the toggle on the opening spring will move the breaker contacts to the open position regardless of the

position of the contacts, exerting the full energy of the opening spring in the process.

No bumper or kick-out springs are used with this type of operator, and the available torque may have a large margin of safety, due to the fact that the opening or closing operation is completed by the straightening out of a hinged toggle

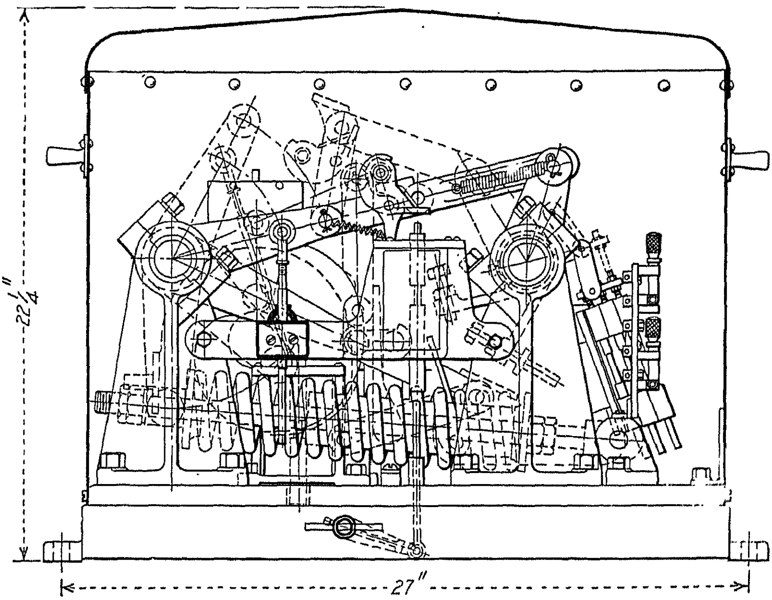


FIG. 107.—Kelman motor mechanism.

link and energy unused is retained in the springs as initial compression.

The speeds of contact movement obtained in actual practice with this type of operator are very high—usually, to the order of 10 or 12 ft. per second on 110,000-volt breakers. As described in the part devoted to modern oil circuit breakers, the Pacific Electric breaker is of the six-break multibreak type, and a contact speed of 10 to 12 ft. per second represents a speed of break of 60 to 70 ft. per second. Such speeds permit accurate synchronizing with 110,000-volt oil circuit breakers, and some operating com-

panies are regularly paralleling high-tension systems by means of high-speed, high-tension oil circuit breakers.

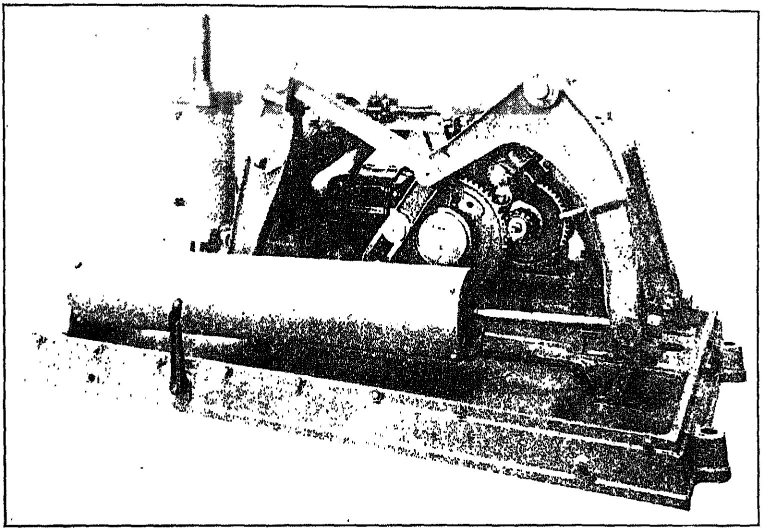


FIG. 108.—Pacific Electric type MW-2 motor-wound spring operator.

There is, also, on record at least one fully automatic synchronizing equipment paralleling high-voltage lines through breakers controlled by this type of operator.

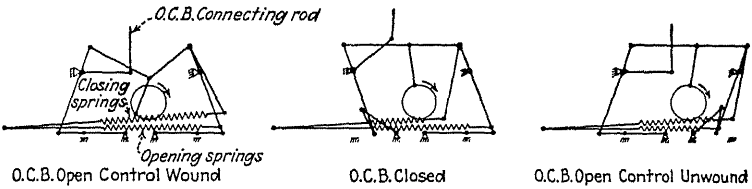


FIG. 109.—Schematic diagram of Pacific Electric operator

General Summary.

The problems of transmission-system stability and the large concentrations of power brought about by interconnected networks have brought to the front the necessity for fast and accurate breaker operation. The oil circuit-breaker

operator is an integral part of the breaker, and it must do its share in the work of the breaker. There is a growing conviction among operating engineers that a great many oil circuit breaker failures have been due to faulty mechanical operation. Either the actuating mechanisms are not sufficiently powerful to function properly after prolonged idleness, with attendant corrosion or gumming up, or they are damaged in action, due to the repeated mechanical shocks incident to repeated operation. It has been stated by some operating engineers that adjustments are much too critical and require "hair-trigger" settings which cannot be maintained in regular operation. A very marked improvement in oil circuit-breaker operators is apparent in the more modern devices offered by the several manufacturers, and it is certain that the next few years will see still further improvements in design if the development of operators is to keep abreast with the development of the breakers themselves.

PART IV

FIELD TESTS

CHAPTER XVII

TESTS

General.

FROM the very beginning of the manufacture of circuit-interrupting devices, tests have been made to determine their fitness for the duty proposed before definitely placing them in a position where the safety of life and equipment depended on their proper functioning. These tests were, of necessity, made under operating conditions, usually in the position in which the device was ultimately to function, and the results recorded as to whether the device functioned satisfactorily, *i.e.*, cleared the circuit without evidences of failure in the device itself. Such tests were carried out on the 5,000-hp., 2,300-volt switches at Niagara in 1894 to 1895 and, later on the 12,000-volt Metropolitan Railway circcuit breakers in 1897. Both types of breakers have been mentioned in the historical part of this book and are illustrated in Figs. 1, 5, and 6.

As circuit-breaker design became more and more important, the several manufacturing companies developed means of obtaining data from factory tests to take the place of service tests, in order to expedite changes in design necessary to overcome troubles developed in operation on the customer's systems.

With the advent of high-tension oil circuit breakers, factory tests giving anything like a reasonable representation of operating conditions were no longer possible. Also, since the high-tension networks in existence comprised the backbone of the systems in which they were a part, operating companies were loath to use them for tests on oil circuit breakers. This forced the oil circuit breaker design engi-

neers to draw conclusions from results of tests on low-voltage breakers as to what would happen to high-tension oil circuit breakers under similar conditions, designing the breaker in accordance therewith and awaiting results from actual operation on the high-tension network.

At the end of 1920, this condition still existed, and there was a growing discontent on the part of those responsible for the operation of several high-tension networks with the entire oil circuit-breaker situation. This discontent was evidenced at numerous conventions of the A. I. E. E., where active discussion followed the presentation of any paper on the subject of oil circuit breakers. Numerous excerpts from these discussions have been quoted at the conclusion of the part of this book devoted to theory and discussion.

Prior to 1920, several companies, notably the Detroit Edison Company, had made tests on oil circuit breakers designed for service below 25,000 volts, but the results were not published.

BALTIMORE TESTS

Late in 1920 and early in 1921, tests were made at Baltimore on 13,200-volt, 25-cycle oil circuit breakers, and the results were published by Louis and Bang (58). This is the first set of tests given full A. I. E. E. publicity where adequate oscillographic apparatus was available to determine definitely what the performance was under the test conditions.

ALABAMA POWER CORPORATION TESTS

The first tests on high-tension oil circuit breakers (above 25,000 volts) in which the results were made public and where adequate recording equipment was used were made on the system of the Alabama Power Company, in 1922. The following summary of the tests on a Westinghouse type G–11 oil circuit breaker is taken from the published account of the Alabama tests (59) and is shown in Table X.

TABLE X.—SUMMARY OF TESTS ON A WESTINGHOUSE TYPE. G-11 BREAKER
Alabama Power Company

Test number	Opened circuit	A		B		C	
		Current opened first arc, cycle r.m.s., amp.	Cycles of arcing	Current opened first arc cycle r.m.s., amp.	Cycles of arcing	Current opened first arc cycle r.m.s., amp.	Cycles of arcing
24	O.K.	894	4.0	900	5.0		
25	O.K.	985	2.5	1,030	....	1,060	
26	O.K.	1,470	3.0				
27	O.K.	1,495	5.0	1,540	....	1,080	
28	O.K.	1,810	5.0	1,850	....	1,790	
29	O.K.	2,030	7.0	....	....	2,225	
30	O.K.	2,500	7.0				
48	O.K.	....	....	....	....	2,640	13.0
49	O.K.	....	....	....	....	2,850	8.0

The same source supplies the data for the summary of tests of a General Electric type FKO–22A breaker rebuilt with explosion chambers shown on next page.

OHIO POWER COMPANY TESTS

Canton Tests.

Later, a series of tests on high-voltage oil circuit breakers was conducted on the system of the Ohio Power Company at Canton, Ohio, and the results presented before the mid-winter convention of the A. I. E. E., in 1927. They are probably the most complete set of high-voltage oil circuit breaker tests on which the data have been published, and they were arranged in three distinct groups as follows:

The first group was performed early in 1925, at which time a 150,000-volt Brown Boveri type AF–24/1A, ten-break oil circuit breaker was tested on balanced three-phase

short circuit. The results as published are set down in Table XII.

TABLE XI.—SUMMARY OF TESTS ON A GENERAL ELECTRIC TYPE FKO-22A BREAKER

R.m.s., amp.	Equivalent kva., three-phase	Arc length, inches	Contracts Speed, ft. per sec.	Oil throw	Signs of distress	Approximate generators connected, kva.
220	38,100	4.6	4.87	None	None	70,000
445	84,800	3.95	4.65	None	None	86,000
1,215	231,000	8.35	5.56	1 pt.	None	70,000
1,225	233,000	8.74	....	None	None	114,000
1,560	297,000	7.87	5.48	1 pt.	None	70,000
1,710	326,000	7.65	6.64	1 pt.	None	86,000
1,720	327,500	8.35	5.75	1 pt.	None	144,000
1,935	368,300	7.46	5.75	2 qt.	None	114,000
2,010	382,500	8.86	6.25	1 qt.	None	114,000
2,180	415,000	7.35	6.25	1 qt.	None	114,000
2,220	422,500	7.66	6.30	1 pt.	None	114,000
2,220	422,500	8.23	6.40	1 pt.	None	114,000
2,225	424,000	10.00	6.55	1 pt.	None	114,000

During the same year, tests were made on a 135,000-volt General Electric type FHKO–39–B breaker with explosion-chamber contacts. The results are shown in Table XIII.

Late in 1925 and during 1926, tests were also made on a 135,000-volt General Electric type FHKO–136–B breaker with explosion-chamber contacts. This breaker failed on test and was modified and repaired and again failed, as shown in Table XIV. The explosion chambers were then redesigned and the breaker again tested, with results as shown in Table XV.

These tests were on a competitive basis to determine whether or not the breakers would meet certain rupturing-capacity requirements, and purchase of equipment was influenced by the results of the tests. The greatest possible

care was exercised in the conduct of the tests, and the best available equipment employed in the securing of data. Such tests are of real value to the industry.

Fundamentally, high-voltage oil circuit breakers are purchased and used solely for the control and operation of high-voltage transmission systems. The effect on the system network is the result which the purchase price is meant to secure. The effect on the breaker itself is incidental. Most tests are made to ascertain whether or not the breaker can withstand the stresses incidental to clearing trouble, and the effect on the network is not considered as a part of the tests. A breaker so slow in operation that it permits the system voltage to fall to a point where stability is lost may succeed in clearing the trouble successfully, as far as the breaker itself is concerned, but it is not a satisfactory breaker from the system operator's standpoint. If this same breaker be speeded up to the point where it will interrupt the circuit before the transmission network is shaken apart, it may fail. Thus, high-voltage oil circuit breaker tests must take into consideration other factors than the behavior of the breaker itself if its suitability for a given installation is to be determined.

In the Canton tests referred to, the effects on the system network are given as qualitative results only, and the result on the oil circuit breakers is quantitative. This was in accordance with the expressed purpose of the test, which was to compare the relative rupturing capacities of the breakers tested. For specific comments on the tests, the original paper should be studied (60).

It will be well to analyze, so far as possible, the results of the Canton tests in the light of the discussion of oil circuit-breaker theory set forth in the second part of this book.

TABLE XII.—RESULTS OF TESTS ON 150-KV. BROWN BOVERI OIL CIRCUIT BREAKER

Duty cycle and system set-up	Test No.	Test voltage	Recovery volts: Peak value line 2–3	Recovery volts: Per cent initial	Current: Closing: Peak	Current: Closing: R.m.s.	Current: Initial in arc, r.m.s.	Duration of short-circuit, half cycles: Total*	Duration of short-circuit, half cycles: Arcing	Short-circuit kva.: Closed	Short-circuit kva.: Opened	Remarks
2-OCO 2-min. interval 4 gen. at Windsor, 2 lines, 2 banks, reactors in.	1	140,000	177,000	89.2	......	......	......	......	......	....	....	Opened O. K. Trace of smoke.
	2	140,000	192,000	97.0	1,990	1,190	940	43	20	288,000	288,000	
1-OCO to test oscillograph. Same set-up as test 1.	3	150,000	No record	......	Could not be read		1,020	44	15	....	283,000	Opened O. K. Trace of smoke.
2-OCO 2-min. interval. Same set-up, except no reactors at Windsor and 2 condensers at Canton.	4	132,000	No record	......	3,740	2,160	1,260	38	14	492,000	288,000	Opened O. K. Trace of smoke.
	5	130,000	104,400	57.8	Could not be read		1,320	37	13	....	297,000	
8-OCO in rapid succession. Interval approx. 10 sec. System same as test 4.	6	135,000	No oscillogram taken			......	......	......	......	....	....	Opened O. K. Trace of smoke.
	7	135,000	No oscillogram taken			......	......	......	......	....	....	
	8	135,000	No record	......	4,160	2,400	1,420	36	12	560,000	332,000	
	9	135,000		......	Could not be read		1,435	38	14	....	335,000	
	10	135,000		......	3,630	2,160	1,435	40	15	520,000	335,000	
	11	135,000		......	4,270	2,490	1,320	37	14	582,000	309,000	
	12	135,000		......	3,740	2,170	1,435	36	13	507,000	335,000	
	13	135,000		......	3,310	2,010	1,455	36†	13†	470,000	340,000	

2-OCO 2-min. system as in Fig. 1‡, except Cleveland off and 22,000-kva. gen. only at Akron. 4 gen. at Windsor.	14	134,000	134,000	70.7	Could not be read		2,340	40	14	....	534,000	Opened O. K. Some smoke, slight oil throw. Noticeable jumping of all three tanks.
	15	134,000	111,000	58.5	6,920	4,000	2,180	38	13	930,000	505,000	
	16	135,000	196,000	103.0	......	No record						Opened O. K. Some smoke, slight oil throw. Noticeable jumping of all three tanks.
2-OCO 2-min. interval. System set-up as in Fig. 1‡, except 22,000-kva. gen. at Akron omitted.	17	135,000	166,500	87.3	......	No record						Opened O.K. Much smoke on tank No. 1 and violent jumping. Other tanks same as above.
2-OCO 2-min. system same as test 16, except only 4 gen. at Windsor.	18	Oscillogram no good				......	......	......	......	....	....	Opened O. K. Some smoke. Considerable jumping.
	19	Oscillogram no good				......	......	......	......	....	....	
	20	132,000	262,000	140.0	8,000	4,680	2,830	34	14	1,070,000	645,000	
	21	132,000	164,000	87.0	7,930	4,580	2,800	37	16	1,040,000	640,000	
	22	132,000	No record	......	7,750†	4,480†	2,830	No record		1,020,000	645,000	
7-OCO 1-min. interval. System same as test 18.	23	132,000	180,000	96.5	6,660	4,020	2,830	40	17	926,000	645,000	Opened O. K. Some smoke. Considerable jumping.
	24	132,000	No record	......	7,000†	4,150†	2,860	No record		946,000	652,000	
	25	132,000	144,000	77.0	Could not be read		2,920	39	16	....	666,000	
	26	132,000	217,000	116.0	8,450	4,900	2,920	34	13	1,120,000	666,000	

* Estimated from current and voltage record. † Estimated, record cut off. ‡ Refer to the original A. I. E. E. paper.

TABLE XIII.—RESULTS OF TESTS ON GENERAL ELECTRIC TYPE FHKO-39B, 135-KV. BREAKER

Duty cycle and system set-up	Test No.	Test voltage	Recovery volts across pole 2				Current						Duration of short, half cycles		Arc length, inches	Short-circuit kva.			Remarks
			G. E. Co.		Dyche		Closing				Initial in arc, r. m. s.					Closed	Opened		
							G. E. Co.		Dyche										
			Peak volts	Per cent initial	Peak volts	Per cent initial	Peak	R.m.s.	Peak	R.m.s.	G. E. Co.	Dyche	Total	Arc-ing		G. E. Co.	G. E. Co.	Dyche	
Trial shot 1-OCO 2 gen. at Windsor...	1	132,000	82,500*	76.5	90,000	83.5	Films could not be read				......	......	39.0	15.0	......	....	....	....	Opened O. K.
8-OCO 30- to 40-sec. interval except between 5 and 6. 2 min. to change film. 2 gen., 2 lines, 2 banks at Windsor. 1 gen., 2 banks, 2 lines at Philo.	2	132,000	96,500	90.0	105,500	93.2	1,870 2,455 2,050	1,365 1,565 1,380	2,390	1,530	1,080 1,150 1,120	1,160	39.0	16.0	11	357,000	263,000	265,000	Opened O. K.
	3	132,000	No G. E. film	......	95,200	88.3	......	......	2,500	1,490	......	1,100	37.8	16.0	......	341,000‡	....	252,000	Opened O. K.
	4	132,000	No G. E. film	......	86,700	80.4	......	......	2,710	1,580	......	1,175	39.0	16.0	......	361,000‡	....	269,000	Opened O. K. Trace of smoke.
	5	132,000	No G. E. film	......	88,500	82	......	......	2,290	1,440	......	1,130	39.4	16.0	......	329,000‡	....	258,000	Opened O. K. Trace of smoke.
	6	132,000	96,500	90.0	90,000	83.5	1,975 †	1,400	2,910	1,580	1,080 1,140 1,070	1,120	37.0	16.0	11	320,000	260,000	256,000	Opened O. K. Trace of smoke.
	7	132,000	No G. E. film	......	95,200	88.2	......	......	2,080	1,370	......	1,130	39.0	16.0	......	312,000‡	....	258,000	Opened O. K. Trace of smoke.
	8	132,000	No G. E. film	......	88,500	82.0	......	......	1,830	1,290	......	1,100	47.0	19.0	......	295,000‡	....	252,000	Opened O. K. Trace of smoke.

	9	132,000	98,000	91.5	No record	......	†	......	2,870	1,660	1,080 1,175 1,135	1,100	43.0	19.0	12.9	380,000‡	263,000	252,000	Opened O. K. Trace of smoke.
2-OCO 2-min. interval full system.§	10	132,000	83,000	77.5	78,000	72.5	4,760 6,350 6,560	3,250 3,670 3,860	8,680	5,030	2,720 2,930 3,010	3,410	35.5	13.0	11.6	885,000	670,000	780,000	Opened O. K. No smoke.
	11	132,000	81,000*	75.0	156,000	145	4,675 6,840 6,475	3,300 2,990 3,785	8,680	5,050	Film blank	3,410	34.0	13.0	......	910,000	Film blank	780,000	Opened O. K. Some smoke
2-OCO 1-min. interval full system.§	12	132,000	78,000	73.0	No Dyche film	......	6,360 5,740 6,900	3,900 3,620 4,080	......	......	2,730 2,840 2,790	......	38.0	14.0	8.8	930,000	640,000	....	Opened O. K.
	13	132,000	No films	......	....	......	......	......	......	......	......	......	......	......	......	....	....	....	Opened O. K.
7-OCO 1-min. interval, except between 17 and 18. 2 min. to change film. Full systems.	14	132,000	66,700	62.5	74,700	69.3	7,550 7,540 5,800	4,375 4,740 3,730	8,920	4,900	2,220 2,360 2,290	2,880	52.0	15.0	8.8	1,080,000	538,000	640,000	Opened O.K.
	15	132,000	No films	......	....	......	......	......	......	......	......	......	......	......	......	....	....	....	Opened O. K.
	16	132,000	No films	......	86,700	80.5	......	......	8,820	5,150	No film	3,510	37.0	15.0	......	1,173,000‡	....	803,000	Opened O. K.
	17	132,000	78,000	73.0	No Dyche film	......	7,025 6,240 7,860	4,180 2,820 4,220	......	......	2,780 2,960 2,840	......	36.0	14.5	10.5	965,000	675,000	....	Opened O. K. Puff of smoke tank 3
	18	132,000	81,500	76.0	104,000	96.5	5,840 6,960 5,530	3,470 4,100 3,620	8,350	4,970	2,780 2,960 2,840	3,450	36.0	12.0	8.8	940,000	675,000	789,000	Opened O. K. Some smoke
	19	132,000	100,000	93.5	118,000	109.5	8,350 6,170 7,450	4,825 3,960 4,340	7,190	4,440	2,680 2,840 2,740	3,380	36.0	13.0	7.6	1,100,000	650,000	773,000	Opened O. K. Some smoke
	20	132,000	81,000*	75.5	90,000	83.5	5,700 7,170 7,320	3,740 4,150 4,250	7,890	4,570	2,780 2,980 2,870	3,450	34.0	12.0	10.5	970,000	680,000	789,000	Opened O. K. Some smoke.

* Obtained from line voltage (arc voltage record N. G.). † Curves off film. ‡ Closed short circuit kilovolt-amperes from Dyche films. § "Full system" means the set-up shown in Fig. 1, of the original A. I. E. E. Paper, minus the 22,000-kva. generator at Akron.

TABLE XIII.—(*Continued*)

Duty cycle and system set-up	Test No.	Test voltage	Recovery volts across pole 2: G. E. Co.: Peak volts	Recovery volts across pole 2: G. E. Co.: Per cent initial	Recovery volts across pole 2: Dyche: Peak volts	Recovery volts across pole 2: Dyche: Per cent initial	Current: Closing: G. E. Co.: Peak	Current: Closing: G. E. Co.: R.m.s.	Current: Closing: Dyche: Peak	Current: Closing: Dyche: R.m.s.	Current: Initial in arc, r. m. s.: G. E. Co.	Current: Initial in arc, r. m. s.: Dyche	Duration of short half cycles: Total	Duration of short half cycles: Arc-ing	Arc length, inches	Short-circuit kva.: Closed G. E. Co.	Short-circuit kva.: Opened: G. E. Co.	Short-circuit kva.: Opened: Dyche	Remarks
2-CO 2-min. interval, full system.†	21	132,000	111,200	104.0	No Dyche film	......	5,040 5,450 5,250	3,420 3,820 3,510	......	......	2,915 2,980 2,960	......	30.0	11.0	9.3	875,000	680,000	......	Opened O. K.
	22	132,000	91,200	85.0	104,000	96.5	7,155 7,320 5,550	4,455 4,360 3,670	9,050	5,320	2,900 3,020 2,960	3,610	31.0	13.0	9.9	1,020,000	690,000	826,000	Opened O. K.
4-OCO 2-min. interval, full system,§ short circuit ungrounded.	23	132,000	63,700*	59.5	No Dyche film	......	5,700 8,340 7,460	3,580 4,800 4,340	......	......	2,625 2,840 2,740	......	40.5	14.0	9.9	1,100,000	650,000	......	Opened O. K.
	24	132,000	93,500	87.5	No Dyche film	......	5,550 5,740 7,180	4,375 2,820 4,170	......	......	2,760 2,900 2,790	......	34.0	13.0	9.9	1,000,000	665,000	......	Opened O. K.
	25	132,000	100,000	93.5	No Dyche film	......	6,240 7,600 6,220	3,740 4,450 3,870	......	......	2,785 2.960 2,870	......	37.0	13.5	9.9	1,020,000	675,000	......	Opened O. K. Some smoke
	26	132,000	86,700*	80.6	No Dyche film	......	7,155 7,170 5,380	4,190 4,220 3,760	......	......	2,810 3,010 3,010	......	40.0	14.0	11	965,000	690,000	......	Opened O. K. Some smoke.

* Obtained from line voltage (arc voltage record N. G.). † Curves off film. ‡ Closed short circuit kilovolt-amperes from Dyche films. § "Full system" means the set-up shown in Fig. 1, of the original A. I. E. E. paper, minus the 22,000-kva. generator at Akron.

TABLE XIV.—RESULTS OF TESTS ON GENERAL ELECTRIC TYPE FHKO-136 B-135-KV. BREAKER
Dec. 6, 1925, and Jan. 10, 1926

Duty cycle and system set-up	Test No.	Test voltage	Recovery volts across pole 2: G. E. Co. Peak volts	Recovery volts across pole 2: G. E. Co. Per cent initial	Recovery volts across pole 2: Dyche Peak volts	Recovery volts across pole 2: Dyche Per cent initial	Current: Closing G. E. Co. Peak	Current: Closing G. E. Co. R.m.s.	Current: Closing Dyche Peak	Current: Closing Dyche R.m.s.	Current: Initial in arc, r.m.s. G. E. Co.	Current: Initial in arc, r.m.s. Dyche	Duration of short half cycles: Total	Duration of short half cycles: Arcing	Short-circuit kva.: Closed G. E. Co.	Short-circuit kva.: Opened G. E. Co.	Short-circuit kva.: Opened Dyche	Remarks
Trial shot 1-OCO 2 gen. at Windsor	27	143,000	......	......	No record	......	......	......	Could not be read	......	715	770	36.0	14.0	....	177,000	191,000	Opened O. K. Part of G. E. oscillograph equipment injured by high voltage from shunts.
Beginning of 8-OCO 30-sec. interval. 3 gen. at Windsor. Reactors in circuit.	28	140,000	100,000	93.0	No record	......	......	......	2,500	1,440	950	930	41.0	14.0	350,000†	230,000	226,000	Opened O. K. Slight jar.
	29	......	......	......	......	......	Breaker did not close											
	30	140,000	115,000	107.0	No record	......	......	......	1,930	1,110	704	700	55.0	18.0	270,000†	171,000	170,000	Opened O. K. Heavier jar.
	31	140,000	90,000	84.0	No record	......	......	......	2,030	1,470	950	Film cut off short	No record		357,000†	230,000	....	Heavy smoke on middle tank, which split open around bottom weld, letting oil escape. Test discontinued.
Trial shot 1-OCO 3 gen. at Windsor.	32*	137,000	No record	......	No record	......	1,700 1,940	985 1,120	1,790	1,100	702 685	780	41.0	13.0	265,000	167,000	185,000	Opened O. K.
Beginning of 8-OCO 30-sec. interval. 3 gen. at Windsor.	33	134,000	No record	......	No record	......	1,780 1,640 1,840	1,070 973 1,060	1,570	990	700 668 705	740	No record		256,000	164,000	172,000	Opened O. K.
	34	132,000	No G.E. films	......	No record	......	......	......	1,490	920	......	710	No record		211,000†	....	163,000	Opened O. K.
	35	131,000	No G.E. films	......	No record	......	......	......	2,040	1,180	......	720	No record		268,000†	....	193,000	Sharp report. Fire from vents on pole 3, much smoke. High-side bushing broken on this pole. Tank bulged, oil level dropped 3 in. Test discontinued.

* Tests 32 to 35, inclusive, made on Jan. 10, 1926. † Closed short-circuit kilovolt-amperes from Dyche films.

TABLE XV.—RESULTS OF TESTS ON GENERAL ELECTRIC TYPE FHKO-136 B-135-KV. BREAKER
May 23, 1926

Duty cycle and system set-up	Test No.	Test voltage	Recovery volts across pole 2				Current						Duration of short half cycles		Arc length, inches	Short-circuit kva.			Remarks
			G. E. Co.		Dyche		Closing				Initial in arc, r.m.s.					Closed G. E. Co.	Opened		
							G. E. Co.		Dyche										
			Peak volts	Per cent initial	Peak volts	Per cent initial	Peak	R.m.s.	Peak	R.m.s.	G. E. Co.	Dyche	Total	Arc-ing.			G. E. Co.	Dyche	
Trial shot 1-OCO 3 gen. at Windsor.	36	140,000	114,000	110.0	97,800	86.0	1,570 1,440 1,700 1,370*	915 1,020 980 970	1,620	1,060	693 720 693 730	740	57.5 56.0 55.0 56.0	22.0 22.0 22.0 22.0	13.5	247,000	175,000	178,000	Opened O. K. No smoke, slight jar.
Attempt to get 8-OCO. Second shot did not close.	37	140,000	126,000	110.0	109,000	96.0	1,440 1,680 1,440 1,430*	955 1,175 980 1,005	1,780	1,110	785 805 785 765	780	52.0 51.0 55.0 51.0	20.5 19.0 21.5 19.0	10.0	285,000	195,000	189,000	Opened O. K. No smoke, slight jar.
Second attempt to get a 8-OCO. Failed to close after 2 shots.	38	140,000	126,000	110.0	No record	......	1,830 1,440 1,700 1,370*	1,085 1,020 1,110 970	1,430	965	760 805 785 730	760	53.0 54.0 52.0 54.0	17.5 19.0 18.0 19.0	11.7	269,000	195,000	184,000	Opened O. K. No smoke, slight jar.
	39	140,000	No G.E. films	......	No record	......	......	......	1,840	1,070	......	750	55.0	19.0	......	260,000	......	182,000	Opened O. K. No smoke, slight jar.
8-OCO 39-sec. interval except 2-min. interval between 43 and 44 to	40	140,000	114,000	100.0	†	......	1,700 2,040 1,570 1,940*	1,020 1,200 1,070 1,130	2,100	1,240	785 805 785 730	785	53.0 53.0 52.0 53.0	21.5 22.0 22.0 22.0	11.5	291,000	195,000	191,000	Opened O. K. No smoke, slight jar.

change film. 3 gen. at Windsor.	41	140,000	NoG.E. films	......	135,000	121.0	......	......	1,740	1,100	......	765	54.5	22.0	......	267,000*	....	186,000	Opened O. K. Some smoke.
	42	140,000	NoG.E. films	......	127,000	114.0	......	......	1,860	1,100	......	750	56.0	22.0	......	268,000*	....	182,000	Opened O. K. Some smoke.
	43	140,000	134,000	118.0	135,000	121.0	1,830	1,070	1,970	1,150	760	760	54.5	20.5	11.0	288,000	195,000	184,000	Opened O. K. Some smoke.
							2,040	1,190			805		55.0	21.0					
							1,960	1,165			785		57.0	22.0					
							1,940*	1,130			730		55.0	22.0					
	44	140,000	107,000	94.0	103,000	92.7	1,700	1,020	1,870	1,090	745	760	54.0	21.5	11.7	298,000	195,000	184,000	Opened O. K. Some smoke.
							2,040	1,190			805		54.0	22.0					
							1,960	1,230			785		55.5	22.0					
							1,960*	1,120			730		54.0	21.0					
	45	140,000	NoG.E. films	......	119,000	107.0	......	......	2,040	1,180	......	760	53.0	22.0	......	286,000	....	184,000	Opened O. K. Some smoke.
	46	140,000	NoG.E. films	......	....	......	......	......	1,600	1,030	......	760	57.0	22.0	......	250,000	....	184,000	Opened O. K. Some smoke.
	47	140,000	100,000	88.0	No record	......	1,700	1,045	1,770	1,090	785	755	61.5	23.5	13.0	269,000	195,000	183,000	Opened O. K. Some smoke.
							1,560	1,020			805		60.0	22.0					
							1,570	1,110			785		54.0	15.5					
							1,485*	950			730		60.0	22.0					
2-OCO 2-min. interval. Full system.	48	138,000	120,000	106.0	103,500	103.0	5,240	3,120	6,880	4,000	2,220	2,280	46.0	14.0	6.8	830,000	569,000	545,000	Cleared easily. Moderate jar, no smoke.
							6,000	3,480			2,380		46.0	14.0					
							6,020	3,480			2,320		48.5	15.5					
							5,700*	3,300			2,200		46.0	14.0					
	49	138,000	103,000	91.0	78,700	78.3	5,630	3,300	6,540	3,820	2,140	2,310	52.5	18.5	8.5	841,000	556,000	552,000	Cleared easily. Moderate jar. no smoke.
							6,000	3,520			2,330		50.0	16.0					
							4,450	3,060			2,320		47.5	13.5					
							5,030*	2,980			2,200		50.0	16.0					

* Values obtained from CT in series with shunt in line 2. † No films for tests 57, 58, 61, and 62.

TABLE XV.—*Continued*

Duty cycle and system set-up	Test No.	Test voltage	Recovery volts across pole 2: G. E. Co. Peak volts	Recovery volts across pole 2: G. E. Co. Per cent initial	Recovery volts across pole 2: Dyche Peak volts	Recovery volts across pole 2: Dyche Per cent initial	Current: Closing G. E. Co. Peak	Current: Closing G. E. Co. R.m.s.	Current: Closing Dyche Peak	Current: Closing Dyche R.m.s.	Current: Initial in arc, r.m.s. G. E. Co.	Current: Initial in arc, r.m.s. Dyche	Duration of short half cycles: Total	Duration of short half cycles: Arc-ing.	Arc length, inches	Short-circuit kva.: Closed G. E. Co.	Short-circuit kva.: Opened G. E. Co.	Short-circuit kva.: Opened Dyche	Remarks
2-OCO 2-min. interval. Full system.	50	173,000	95,000	85.0	118,200	105.0	6,550	3,800	4,840	3,140	2,440	2,450	39.0	14.0	8.0	901,000	615,000	582,000	Cleared easily. Moderate jar.
							4,800	3,190			2,590		37.0	14.0					
							6,550	2,770			2,590		35.5	12.5					
							4,570*	3,040			2,380		37.0	14.0					
	51	137,000	82,000	73.0	98,700	86.3	4,700	3,090	5,620	3,270	2,440	2,490	41.0	15.0	8.0	780,000	602,000	592,000	Cleared easily. Moderate jar.
							5,520	3,290			2,540		38.0	14.0					
							5,500	3,200			2.540		36.0	12.0					
							5,250*	3,100			2,330		38.0	14.0					
4-CO 1-min. interval. Full system.	52	137,000	85,500	76.5	97,200	87.4	5,750	3,390	5,520	3,250	2,320	2.440	40.5	14.5	9.5	895,000	582,000	580,000	Cleared easily. Moderate jar. No smoke.
							5,280	3,190			2,450		41.0	16.0					
							6,550	3,780			2,410		41.0	16.0					
							5,030*	3,060			2,330		41.0	16.0					
	53	137,000	92,500	82.5	99,000	86.6	4,970	3,120	5,900	3,490	2,450	2,600	40.5	17.0	9.2	780,000	602,000	617,000	Cleared easily. Moderate jar. No smoke.
							5,520	3,290			2,540		38.0	16.0					
							4,850	3,090			2,510		39.0	17.0					
							5,150*	3,080			2,420		38.0	16.0					
	54	137,000	95,000	85.0	No record	.....	5,750	3,420	5,570	3,310	2,410	2,450	39.0	13.0	9.5	858,000	602,000	582,000	Cleared easily. Some smoke after ¼ min.
							5,400	3,220			2,500		40.0	16.0					
							6,280	3,620			2,540		36.0	12.5					
							4,580*	7,840			2,330		40.0	16.0					

	55	137,000	105,000	94.0	No record	......	6,550 4,800 5,500 3,890*	3,800 3,240 3,160 2,680	5,000	3,140	2,410 2,450 2,440 2,370	2,490	41.0 39.0 38.0 39.0	14.0 14.0 13.5 16.0	10.0	901,000	582,000	592,000	Cleared easily. Slightly more smoke.
4-CO 1-min. interval. Full system. Ungrounded short.	56	137,000	112,000	100.0	......	......	7,600 4,440 6,930	4,400 3,100 4,000	......	......	2,380 2,500 2,480	......	39.0 39.0 37.0	15.0 15.0 13.0	9.5	1,041,000	592,000	..	Opened O. K. No smoke.
	59†	......	90,000	80.5	......	......	4,450 5,280 5,900	2,900 3,100 3,450	......	......	2,130 2,160 2,170	......	57.0 56.0 56.0	18.0 18.0 17.0	11.0	818,000	515,000	......	Opened O. K. Some smoke (tests 57 and 58 opened O. K.)
4-OCO 1-min. interval. Full system. Ungrounded short circuit.	60	......	99,000	88.3	......	......	4,580 5,520 5,500	2,960 3,360 3,180	......	......	2,410 2,540 2,500	......	42.0 42.0 36.5	19.0 19.0 15.5	8.0	797,000	602,000	......	On this test and also on 61 and 62 opened O. K. Some smoke.
	63†	......	......	......	......	......	4,450 5,640 5,230	2,900 3,340 3,090	......	......	1,900 1,955 1,935	......	60.0 62.0 62.0	17.0‡	......	792,000	464,000	......	Opened O. K. More smoke.
2-CO 2-min. interval. Full system. Ungrounded short circuit.	64	......	......	......	......	......	5,500 4,200 5,500	3,160 2,440 3,230	......	......	2,590 2,640 2,640	......	31.0 31.0 30.0	17.0‡	......	765,000	625,000	......	Opened O. K. Slight smoke.
	65	......	......	......	......	......	4,450 5,640 5,230	3,010 3,260 3,040	......	......	2,590 2,640 2,590	......	33.0 31.5 31.5	17.0‡	......	772,000	625,000	......	Opened O. K. Some smoke.

* Values obtained from CT in series with shunt in line 2. † No films for tests 57, 58, 61, and 62. ‡ No arc-voltage record, values assumed.

The physical comparison of the Brown Boveri and General Electric breakers tested is somewhat as follows:

	General Electric	Brown Boveri
Type	FHKO-39-B	AF 24/1A
Rated voltage	135,000	150,000
Contacts	Explosion chamber	Multibreak
Number of breaks per pole	2	10
Contact travel, inches	30	10
Total break, inches	60	100
Speed of contacts, ft. per sec.	6 to 7	1.7 to 2.2
Average time of arc, half cycles	13.5	15.2
Arc length per contact, inches	9.2	2.8 (est.)
Total length of arc, inches	18.5	28.1 (est.)

As recorded in the published data, the two breakers are considered as equivalent from an operating standpoint. The table gives, in a general way, a comparison between the two types and tends to confirm the Swiss Railway tests quoted in a previous part of the book that the contacts of a two-break breaker must move three and one-half times as rapidly as the contacts of a ten-break breaker to be equally effective in the interruption of a given current. This does not consider the type of contact, depth of oil over contacts, etc. It is quite probable that with two breaks moving at a speed of less than 2 ft. per second, neither breaker would have been able to interrupt the circuit. On the other hand, if the ten-break breaker had had a contact speed of 5 ft. or more per second, the time of arcing would have been greatly reduced. The tests show a degree of equality in interrupting abilities of the two breakers, even with the slow contact speed of the ten-break breaker. With a contact speed equal to that of the two-break breaker, there is no doubt that the multibreak breaker would have performed to better advantage.

From an operating standpoint, it is essential to reduce the arcing time to a minimum. As the time of arcing is

decreased, transmission-system conditions improve. Equipment, lines, and property are saved and the continuity of service is increased, because a line or bus which would be destroyed beyond the point of resuming service by an arcing fault continuing a sufficient length of time will be cleared before the damage is done and is available for intermediate resumption of service as soon as the cause of the arc has been removed. This fact has been demonstrated many times in the past few years on the systems of many operating companies.

Concentrations of power have become so great that any arcing on a transmission-line conductor either burns the conductor until it is parted or so anneals it that it parts due to mechanical strain, if the arc is sustained until the circuit is cleared by manual operation of the oil circuit breakers. If relayed automatically, it is possible and practicable to clear the circuit rapidly enough to prevent damage to either the conductor or insulation, which would be sufficient to prevent the immediate resumption of service. To be successful, such relaying must be both fast and accurate, and if the greater portion of the available time is consumed by the oil circuit breaker itself, the chances of success are decidedly limited.

Several "superpower" transmission systems or networks have been proposed in which there would be unusually high concentrations of power. To be financially successful, such superpower systems must not only handle these large blocks of power but must also maintain a very high load factor. Outages cannot be tolerated, and high-speed switching and the isolation of trouble are vital. The limiting feature to the carrying out of these superpower schemes, as far as the engineering and operation are concerned, lies in the oil circuit breakers. Their reliability is in doubt, and their speed of operation such as to make uncertain the results which would follow any attempts so to relay the system as to prevent damage to equipment by fault currents.

PACIFIC GAS AND ELECTRIC COMPANY TESTS

Preliminary Preparation.

In 1925 and 1926, the Pacific Gas and Electric Company made a practical study of system stability (61), and some attempt was made to secure data on the various types of high-voltage oil circuit breakers in use on the system. In order that the breaker data might be as useful as possible, tests were made on the breakers in actual operation in the high-tension network. Some special apparatus was developed and very careful thought given to the conduct of tests. Among other things were the development of an oscillograph film holder which would handle 30 ft. or more of film and operate at any desired speed up to 30 ft. per second; the use of position indicators on all circuit breakers under observation which recorded on the oscillograph film the exact position of the breaker contacts at any instant during the operation; a 50-cycle tuning fork for timing; and the development of a technique allowing simultaneous oscillograms to be taken at different points on the high-tension network.

The position indicator is shown diagrammatically in Fig. 110 and consisted of two bakelite-mounted brass strips with their edges indented and interlaced in the form of a commutator. A light moving finger contact connected these strips together twice for each commutator gap as it passed back and forth across their face. The finger was attached to the arm carrying the oil circuit-breaker contacts so that with the connections indicated in the figure there resulted a series of current-impulse records on the film corresponding to the times the moving finger short circuited the two parts of the commutator. By breaking up part of the commutator and inserting resistance, these impulse records were caused to change their height on the film at certain points, such, for instance, as at the parting of the main contacts. For the rotating type of switch, a form as shown in Fig. 111 was used, giving similar results.

In the use of such a position indicator, the device is attached to the oil circuit breaker and arranged to cover the total travel. Using the oscillograph visually, the oil circuit

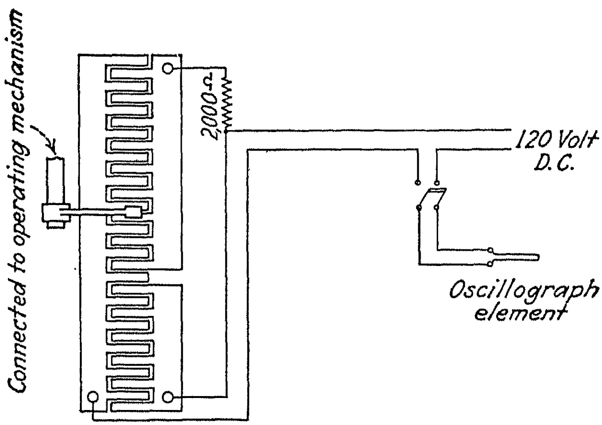


FIG. 110.—Schematic diagram of position indicator for General Electric and Westinghouse breakers.

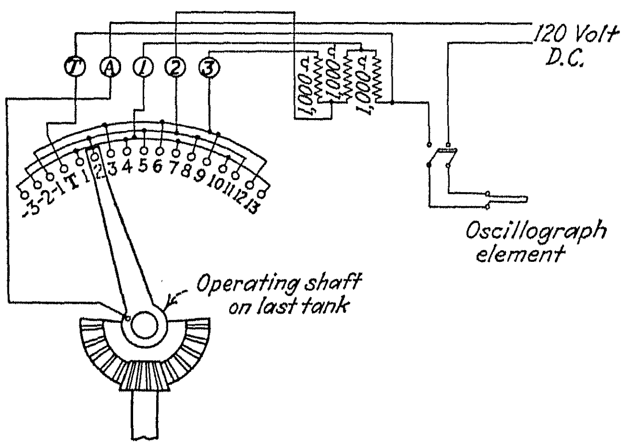


FIG. 111.—Diagram of position indicator used on Pacific Electric breakers.

breaker contacts are moved by hand until the first gap is bridged and the contact travel noted, then moved forward again until the finger breaks contact and the travel noted. In this way, the full travel is recorded and plotted.

It is essential to have at least one change of resistance during the travel of the position indicator, in order definitely to tie one current impulse with a particular position of the breaker and thus fix the entire series of impulses and, consequently, the relation of contact position to the other curves on the oscillograph film. It is best to insert this resistance step at some strategic position, such as the parting of the main contacts or the release of the arcing tips.

After the position indicator has been set as outlined, a low-voltage direct-current source is connected across the oil circuit-breaker terminals and an oscillograph film of the oil circuit-breaker action is made as the breaker is closed and tripped by the control equipment used in regular operation. The film can be plotted in the form of a curve showing inches of travel against time by noting the record of the position indicator and the 50-cycle timing wave. These curves definitely place the point at which contact is made or broken, the elapsed time for any part of the stroke, the speed at any point during the stroke, and the overtravel or rebound if any exists. Curves obtained in this manner are shown in Figs. 90, 96, and 102 in the chapter on operating mechanisms.

The curves thus obtained become the "no-load" or calibration curves of the breakers under test, and when they have been obtained and verified, such operating tests under load as may be desired are conducted with the travel-indicating equipment still undisturbed.

Operating Tests.

The primary purpose of those tests which have been previously referred to as having been completed and the results published was the demonstration of the fitness of the oil circuit breaker for the duty it was purchased to perform. Due to the fact that the several manufacturers had data on balanced three-phase, short-circuit performance, most tests have been scheduled for such conditions either with or without grounding. Several ideas in this connection have

been developed in low-tension testing and carried forward to the higher voltages, *i.e.*:

1. That a balanced three-phase ungrounded short circuit was the worst possible condition, because it would give a higher recovery voltage than the same circuit conditions grounded.
2. That the initial rush of current was the maximum.
3. That the amount of energy to be absorbed by the rupturing equipment was constant.

These points will be taken up and discussed in connection with tests made on the Pacific Gas and Electric Company System in 1926 to 1927, in connection with the studies of system stability.

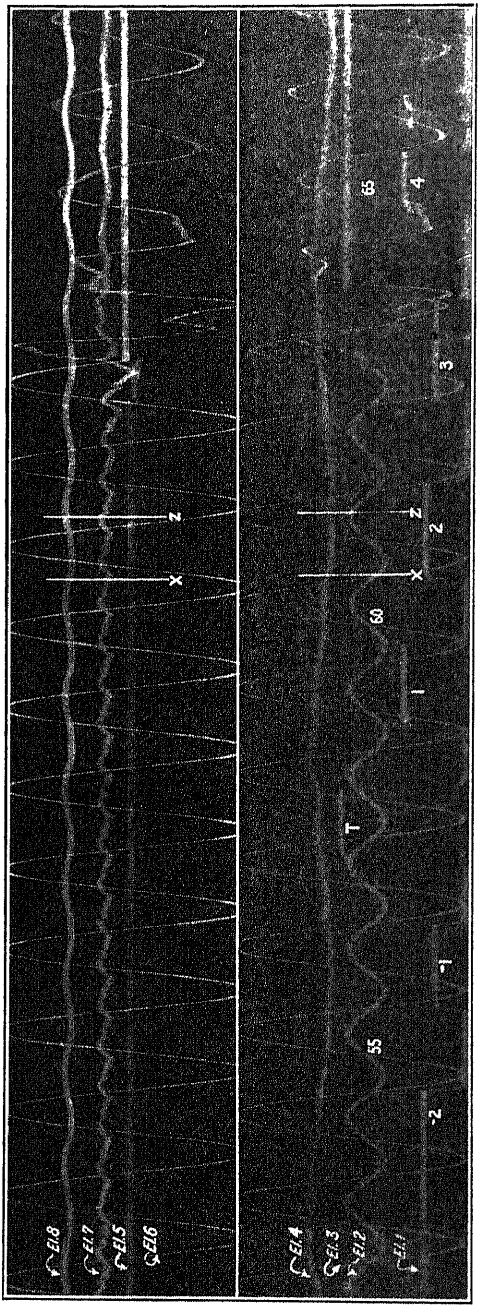
The first of the series was an operating test on a Pacific Electric Manufacturing Corporation 400-amp., 110 kv. oil circuit breaker temporarily placed in the Vaca–Dixon–Cordelia 100-kv. line at Vaca–Dixon substation. This placed about 15 miles of 100-kv. line between the point of short circuit and the oil circuit breaker and reduced the available kilovolt-amperes to approximately 175,000. Oscillograms[1] for the ungrounded test are shown in Fig. 113, and for the grounded test in Fig. 112. A summary of the results of the two conditions gives:

	With short circuit and ground	Short circuit only
Bus volts at Vaca, kv.	115	115
Sustained bus volts at Vaca, kv.	24	24
Maximum amperes	Peak 2,080	Peak 1,760
Amperes ruptured, r.m.s.	975	970
Arc length per contact, in.	2.6[1]	2.3
Velocity of rupture (per contact), ft. per sec.	4.8	4.9
Cycles of arc	3	3

[1]Arc length does not include arcing-tip travel.

[1]All oscillograph calibrations are r.m.s. current measured on the oscillograph deflection.

To determine the current or voltage indicated, measure the distance from the zero of the wave to the peak in the units given on the curve. The result will be an r.m.s. value including all corrections.

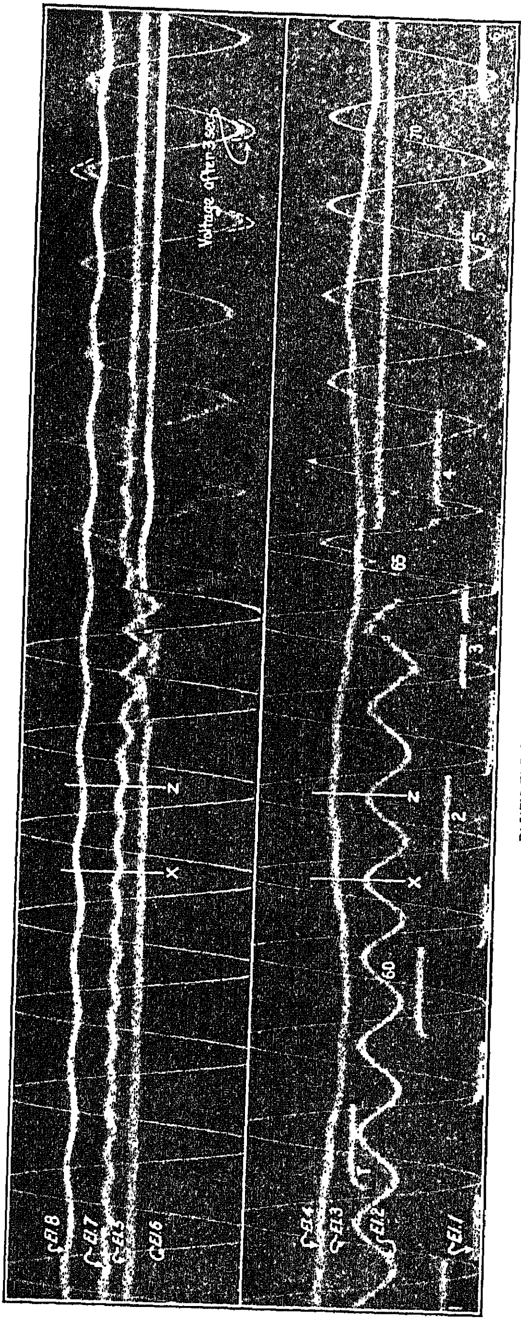


PACIFIC ELECTRIC MFG. CO. 110 KV O.C.B.
INTERRUPTION OF THREE PHASE GROUNDED SHORT CIRCUIT
AT VACA-DIXON SUBSTATION - JUNE 22, 1926

x - A Phase Contacts Open   z - C Phase Contacts Open

El.1 - Position Indicator
El.2 - Aø Volts (to grd.) 0 ___ 50 kv (r.m.s.)
El.3 - Cø Current 0 ___ 500 Amp. (r.m.s.)
El.4 - 60-50 Cycle Timing
El.5 - Arc Volts Aø 0 ___ 50 kv (r.m.s.)
El.6 - Aø Current 0 ___ 500 Amp (r.m.s.)
El.7 - Arc Watts Aø 0 ___ 20,000 kw
El.8 - 50 Cycle Timing

FIG. 112.



PACIFIC ELECTRIC MFG. CO. 110 KV O.C.B.
INTERRUPTION OF THREE PHASE UNGROUNDED SHORT CIRCUIT
AT VACA-DIXON SUBSTATION - JUNE 22, 1926

x - A Phase Contacts Open   z - C Phase Contacts Open

El.1 - Position Indicator
El.2 - A ø Volts (to grd.) 0 ___ 50 kv (r.m.s.)
El.3 - C ø Current 0 ___ 500 Amp. (r.m.s.)
El.4 - 60-50 Cycle Timing
El.5 - Arc Volts A ø 0 ___ 50 kv (r.m.s.)
El.6 - A ø Current 0 ___ 500 Amp. (r.m.s.)
El.7 - Arc Watts A ø 0 ___ 20,000 kw
El.8 - 50 Cycle Timing

FIG. 113.

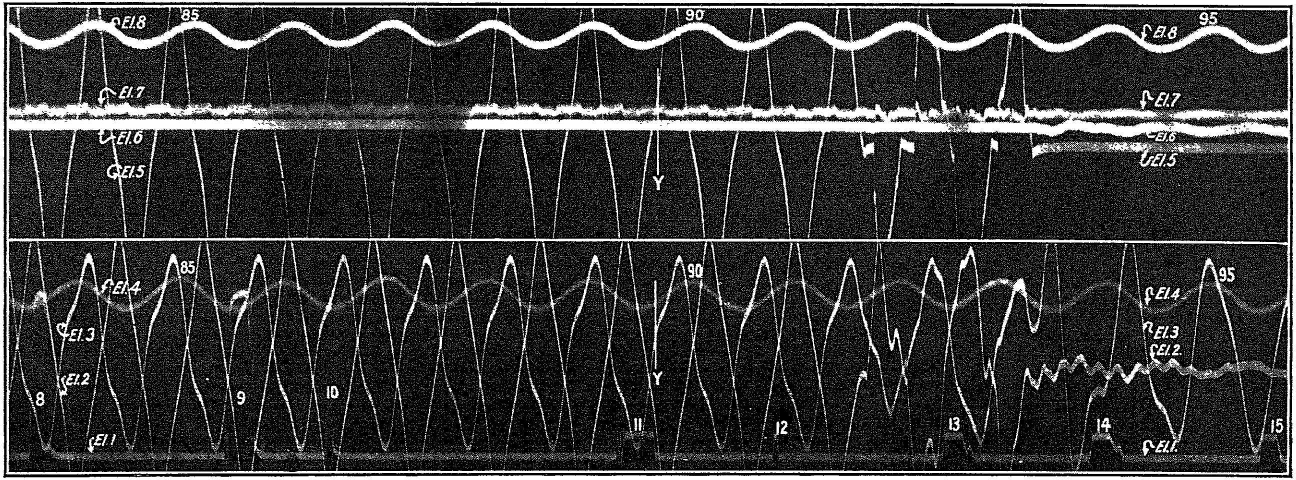
In these tests, the breaker showed no sign of distress in any way. Particular attention should be given to the short time of arcing of about 0.05 sec. in each case. There is evident in the voltage wave a particular resonance to the seventeenth harmonic of 60 cycles coming from the tooth ripple in the Pit No. 1 Power House generators. Its effect is apparently negligible except as an interesting physical phenomenon.

Load-switching Tests.

Following the 100-kv. tests, load-switching tests were made on the 220-kv. transmission lines, using the Westinghouse G–2, 187-kv. oil circuit breaker. The load was about 33,000 kw., requiring 135 amp. of 220-kv. for the normal operating condition. A summary of the results of this test is given in connection with the single-phase ground tests on the same oil circuit breaker, and it will be referred to in comparison with the interruption of 165 amp. of charging current by the same breaker.

Single-phase Ground Tests.

On a transmission network using grounded Y-connected transformers, experience has shown that roughly 95 per cent of the troubles requiring switching are from phase to ground. It is important both from the standpoint of system stability and from that of oil curcuit breaker performance that tests be carried out covering this condition. Such tests were undertaken on the 220-kv. network isolated from the rest of the system. Figure 114 shows the oscillograms on the Westinghouse G–2, 186-kv. oil circuit breaker tripped by relay in the usual operating manner for the isolated condition. This portion of the Pacific Gas and Electric Company System has about 200,000 kva. balanced three-phase available. Figure 115 gives a graphic analysis of the oil circuit breaker action. Here it is seen that the duty is but little



WESTINGHOUSE TYPE G2, 187 KV O.C.B.
INTERRUPTION OF SINGLE PHASE GROUND ON PIT LINE NO. I
(SYSTEM ISOLATED)
AT VACA-DIXON SUBSTATION - JULY 3, 1926

y - B Phase Contacts Open

El. 1 - Position Indicator
El. 2 - Residual Current, Bank No. 1 0 ____ 200 amp. (r.m.s.)
El. 3 - A ø Current, Bank No. 1, 11 kv 0 ____ 1500 amp. (r.m.s.)
El. 4 - 50 Cycle Timing
El. 5 - B ø Line Current 0 ____ 300 amp. (r.m.s.)
El. 6 - B ø Volts (to grd.) 0 ____ 50 kv (r.m.s.)
El. 7 - Arc Watts, B ø 0 ____ 100,000 kw
El. 8 - 50 Cycle Timing

FIG. 114.

more severe than the load switching at 33,000 kw., giving no indication of stress in the oil circuit breakers. Following the isolated ground, the system was connected normally and the G–2, 187-kv. oil circuit breaker closed in on a ground on one-phase and cleared by the station relays, as in normal operation. This test is especially interesting from an operating standpoint, since it represents the procedure and performance for the greater portion of practical breaker operations on transmission troubles. The oscillogram for the beginning and end of this operation is shown in Fig. 116,

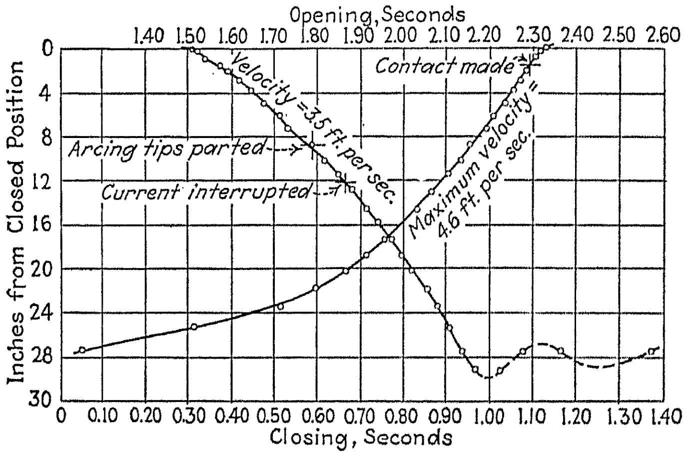
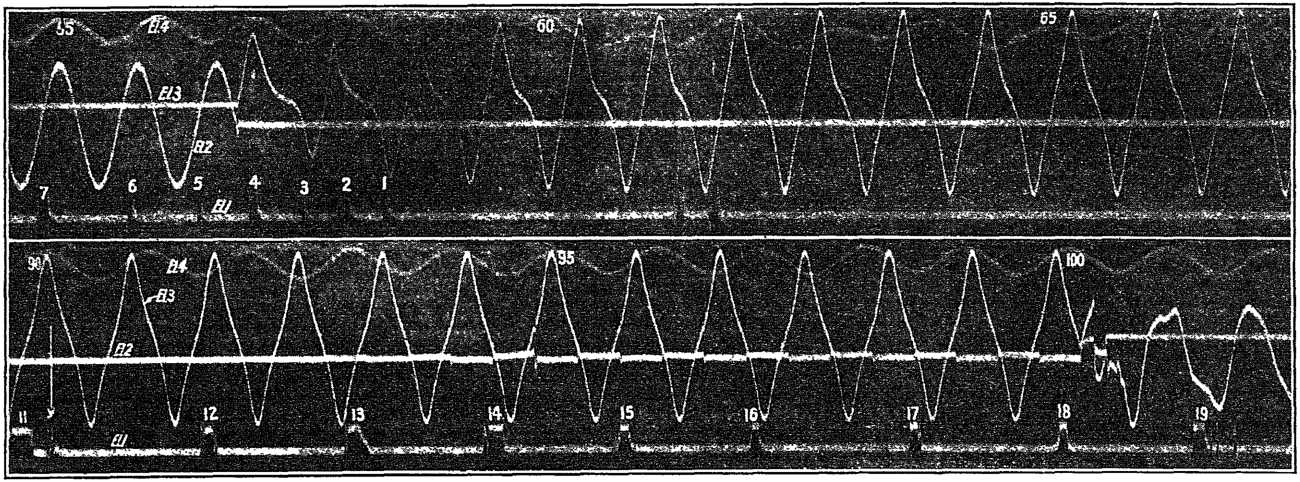


FIG. 115.—Graphic analysis of Fig. 114.

and Fig. 117 is a graphical analysis. On the oscillogram it is to be noted that the short-circuit current is not a maximum immediately after closing the oil circuit breaker but increases for nearly 10 cycles before a steady state is reached. This is due to the phase-balancing, or phase-converting, action of the connected equipment, and the delay is due mostly to the time required to make the necessary magnetic changes. There is indicated on the oscillogram the point at which the contacts part; in this case, they are mechanically unlatched, the exact position is calibrated and located by the position-indicator record. From this point on, the



WESTINGHOUSE TYPE G2 187 KV O.C.B.
INTERRUPTION OF SINGLE PHASE GROUND ON PIT LINE NO.1
(SYSTEM CONNECTED)
AT VACA-DIXON SUBSTATION JULY 9, 1926

y - B Phase Contacts Open

El.1 - Position Indicator
El.2 - Arc Volts B ø 0 ______ 150 kv (r.m.s.)
El.3 - B ø Current 0 ______ 2000 amp. (r.m.s.)
El.4 - 50 Cycle Timing

FIG. 116.

film shows that nearly four cycles are required before there is any indication of an arc, either in voltage across the arc or on the current wave, giving proof that it is dangerous to base conclusions as to arc length on the appearance of the current or voltage record on the oscillograph films. These four cycles represent a main contact travel of some 3 in., during which time the arcing tips were being drawn up in the opposite direction by their springs.

About six cycles after the arcing contacts part, the voltage across the arc seemed to be a maximum, at which time

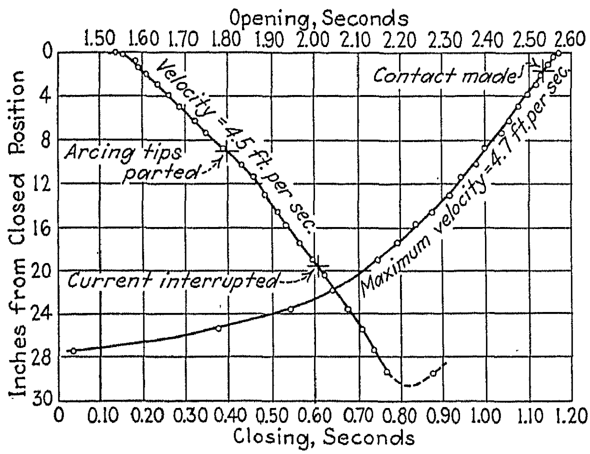


FIG. 117.—Graphic analysis of Fig. 116.

the main contacts had traveled downward 5 in., as is shown in Fig. 117. At the same time, the arcing tips had traveled backward, pulled by their springs to their original position 9 in., as is also shown in Fig. 117.

So far as could be determined, the arcing tips move about twice as rapidly upward as the main contacts move downward, which, when the main contacts had moved down 5 in., would have allowed the arcing contacts to return to rest in their original position. This is substantiated in the curve of the arc voltage, which, at about six cycles after the arcing contacts parted, reached a maximum and then decreased

as the main contacts traveled farther down, until, after 19.6 in. of travel, the arc was broken in much the same manner as on a plain-break oil circuit breaker.

The following is a summary of the load-switching and ground tests:

TESTS ON WESTINGHOUSE TYPE G-2, 187-KV. OIL CIRCUIT BREAKER ON VACA 220-KV. BUS

Single-phase ground at Vaca	Pit units isolated from system	Pit units and system connected
Maximum current in short, amp. (r.m.s.)	600	2,410
Current interrupted	540	2,230
Nominal 3-phase kva	206,000	850,000
Cycles of arc	$4\frac{1}{2}$	$12\frac{1}{2}$
Contact travel before arc was extinguished, in.	4	$11\frac{1}{2}$
Approximate length of arc, in.	18	39
Load-switching test:		
Current interrupted, amp.	...	135
Kw. load	...	33,000
Cycles of arc	...	3
Contact travel before arc was extinguished, in.	...	2.8
Approximate length of arc, in.	...	16

Approximate arc length is estimated on the basis of arcing tip travel at twice the velocity of contact travel for the Westinghouse switches.

LINE-CHARGING CURRENT TESTS

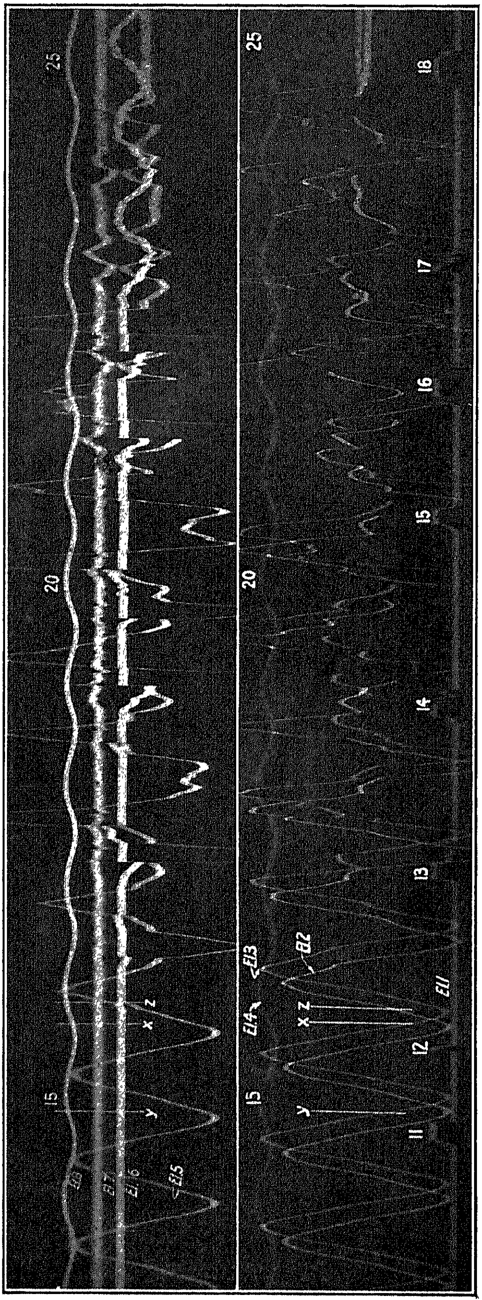
(220-kv. Line)

It had been known for many years that an alternating current at low power factor was more difficult to interrupt than the same at unity power factor. This was explained by the fact that at the zero point in the current wave there was available a considerable voltage to reestablish the current flow, which was not the case at unity power factor.

This held true for all cases observed where the power factor was due to synchronous machinery, whether the current was lagging or leading with respect to voltage. With the advent of the very long high-tension lines of the Pacific Coast, however, a new problem was encountered in line-charging current, though even this for several years gave no particular concern, since the values of current were relatively small. When transmission voltages reached 220-kv., and line lengths more than 200 miles, it became necessary to consider line-charging current interruption as a separate problem.

When interrupting a circuit, it is at present not physically possible to interrupt the several phases simultaneously. Neither is it possible to interrupt the two ends of a transmission line simultaneously, so that for each circuit cleared by oil circuit breakers some breakers must interrupt the charging current, except in the very rare occurrence of a three-phase short circuit. Some study was, therefore, attempted in order to gain an insight into the action of an oil circuit-breaker interrupting charging current.

The oscillographic record of a Westinghouse type G–2, 187-kv. oil circuit breaker used to interrupt the charging current on 202 miles of 220-kv. line is shown in Fig. 118. This is the same oil circuit breaker previously described in interrupting a single-phase ground on the same line. The charging current interrupted was 165 amp. at 220 kv. The length of arc as shown on the curve in Fig. 119 was an average of 18½ in., the velocities of the oil circuit breaker the same as in the short-circuit tests, and the oil pollution about the same. In comparing the two oscillograms, it is at once apparent, on one hand, that the 2,400 amp. or more of short-circuit current keeps its wave form until interrupted; in other words, the arc is a relatively stable current-carrying conductor whose resistance is varied somewhat by the movement of the oil circuit-breaker parts, as has been pointed out. On the other hand, the charging-current arc is highly unstable as regards wave form, and, instead of the 165 amp.



WESTINGHOUSE TYPE G2, 187 KV O.C.B.
PIT LINE CHARGING CURRENT INTERRUPTION AT 220 KV
AT VACA-DIXON SUBSTATION JUNE 26, 1926

x - A Phase Contacts Open   y - B Phase   z - C Phase

El.1 - Position Indicator
El.2 - C∅ Current 0 ___ 200 amp. (r.m.s.)
El.3 - A∅ Current 0 ___ 200 amp. (r.m.s.)
El.4 - 50 Cycle Timing
El.5 - B∅ Current 0 ___ 200 amp. (r.m.s.)
El.6 - Arc Volts B∅ 0 ___ 250 kv (r.m.s.)
El.7 - Arc Watts B∅ 0 ___ 125,000 kw
El.8 - 50 Cycle Timing

FIG. 118.

of relatively smooth sine-wave current before the arc, the current values during the arc extend far off the film to estimated values of over 1,000 amp., with a rate of growth over twelve times that of the normal 60-cycle charging current. In addition, the voltage across the short-circuit arc gives a flat-topped wave, since the voltage across an arc carrying the available current of the length required

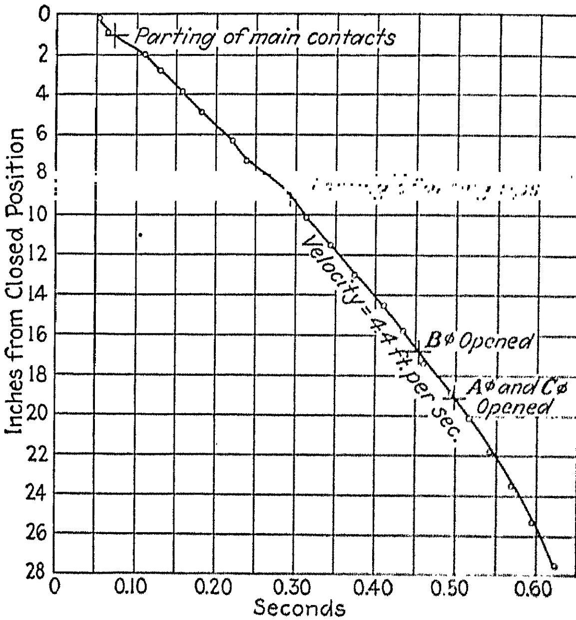


FIG. 119.—Graphic analysis of Fig. 117.

is nearly constant, and it has the familiar "horns" on the wave seen in low-voltage arcs.

The voltage across the contacts of the oil circuit-breaker interrupting charging current builds up to a point where the arc is struck and dies abruptly to zero, while the current builds up at the natural period of the transmission line. Such a phenomenon has been described in detail by several engineers under the term of "frequency conversion" (62). It is the phenomenon which gives a switching surge on a bus

only a few feet long of the same order of magnitude as that on a line several hundred miles long (63).

Contrary to the usual opinion, the action of oil-circuit breakers in interrupting charging currents is of a very considerable importance in present-day high-tension practice and is certain to be much more so as high-tension networks develop and higher voltages for transmission become useful.

Just as in the short-circuit test, the quick-break mechanism reached the end of its stroke and was seated before the arc was interrupted, though the action is not so clearly defined as it was for the short-circuit interruption.

LABORATORY TESTS

It is generally conceded that there are two methods of design for oil circuit breakers, based on

1. Trial and error.
2. Research on fundamental phenomena.

Trial and Error.

Under the first heading come the usual factory and field tests as commonly carried out in the United States.

1. Factory tests allow correction, by change and retrial, of mechanical troubles, magnetic effects, gas-pressure troubles, leakage over insulated surfaces, etc.

2. Field tests allow correction for weather conditions, various duty cycles with resonance, and various recovery voltages.

Such field tests must be carried out under a carefully supervised schedule of which the following is a typical example:

DATA SHEET

ALABAMA POWER COMPANY

Oil Circuit Breaker Interrupting-capacity Tests

Covering tests at ____________ Station, on __________, 19____

on ________________________________ breaker

---

1. Test Circuit

In accordance with diagram of this specification, except as follows:

---

2. System Set-up

Normal -system frequency ____________ cycles

a. Generator Capacity in Service		*b.* Synchronous Load in Service	
Plant	Kva.		Kva.
________	____	Motors	____
________	____	Condensers	____
________	____	Motor generators	____
________	____	Rotaries	____

---

b. System Connections.

DATA SHEET—*Continued*

3a. Calculated Short-circuit Amperes

Initial____________________amperes

After____________________cycles,____________amperes

Final____________________amperes

3b. Calculated Power Factors____________Per Cent

Power factor is defined as the cosine of the angle between the short circuit current and the reestablished voltage.

---

4. Oscillograph Tabulation

	A phase	B phase	C phase
Phase			
C. T. ratio			
Shunt Tap number			
Vib. res., ohms (incl. series res.)			
A. C. amperes			
Deflection, inches (peak to peak)			
Amperes/inch r.m.s.			
P. T. ratio			
Vib. res. (incl. series res.)			
Calib. voltage			
Deflection, inches (peak to peak)			
Volts/inch (maximum)			

DATA SHEET—*Continued*

5. Data on Breaker under Test

Type__________________ Manufacturer____________________

Rating: Voltage__________________

Amperes: Normal__________________ Short time_____________

Interrupting_____________amperes on___________unit, OCO

Operating cycles at_______minute intervals at_______kv.

Kind of oil____

Relay settings: Test breaker____________________________________

Protective breakers______________________________________

Inherent time lag: Breaker only________________________cycles

Breaker with relay______________________________cycles

Height of oil in tanks before tests: Tank______________________

Height ____

Muffler adjustment ____

---

6. Log of Test

Voltage on supply bus before test________________________

Oscillograph films Nos._______________________________

Movie films Nos._____________________________________

Camera plate or film Nos.______________________________

Operating duty of test_________________________________

Exact time of breaker openings:

1st_________ 2nd_________ 3rd_________ 4th_________

Normal voltage test after completion of duty cycle:

Started______________________________________

Finished_____________________________________

Elapsed time____________________________minutes

DATA SHEET—*Continued*

8. Inspection before and after Test

a. Condition of parts of breaker found to be as follows:

Part		Phase A	Phase B	Phase C	Refer to photo or sketch No.
Main contacts	Before				
	After				
Arcing contracts	Before				
	After				
Baffles or liners	Before				
	After				
Tanks	Before				
	After				
Bolts, bands, and straps	Before				
	After				
Lifting rod and mechanism	Before				
	After				
Arcing-contact mechanism	Before				
	After				
Control box and operating mechanism	Before				
	After				
Gaskets	Before				
	After				
Bushings and adapters	Before				
	After				
Dashpots and shock absorbers	Before				
	After				

DATA SHEET—*Continued*

b. Condition of oil found to be as follows:

Item	Phase		
	A	B	C
Height of tank			
Distance from top to oil, before test			
Height of oil, before			
Distance from top to oil, after test			
Difference in height of oil			
Percentage of original oil lost			
Air temperature			
Temperature of oil	Before		
	After		
Dielectric test of oil before			
Dielectric test of oil after			
Kind of oil			

DATA SHEET—*Continued*

c. General remarks:

9. Effect of Short Circuit on System.

Generating stations:

Substations:

Synchronous machinery:

DATA SHEET—*Continued*

10. Data from Oscillograms.

Item	2-CO duty cycle	Phase A	Phase B	Phase C	Film No.
Max. initial r.m.s., amperes	First				
	Second				
Interrupted r.m.s., amp.	First				
	Second				
Cycles from start of short until: *a*. Main contacts open *b*. Arc breaks	First *a*				
	b				
	Sec. *a*				
	b				
Duration of arc in cycles	First				
	Second				
Voltage to neutral, before short (maximum)	First				
	Second				
Reestablished voltage to neutral (maximum), 1st cycle	First				
	Second				
Percentage reestablished voltage to neutral (max.)	First				
	Second				
Phase angle of reestablished voltage with S. C. current	First				
	Second				
Power factor (cosine of above angle)	First				
	Second				

DATA SHEET—*Continued*

Item	2-CO duty cycle	Phase A	Phase B	Phase C	Film No.
Tank pressure, lb./sq. in.	First				
	Second				
Ground current, highest r.m.s. value	First				
	Second				
Phase voltage before short (maximum)	First				
	Second				
Reestablished phase voltage, (maximum), 1st cycle	First				
	Second				
Percentage reestablished phase voltage	First				
	Second				
Watt-seconds per arc	First				
	Second				
Speed of contacts, ft./sec.: Closing	First				
	Second				
Speed of contacts, ft./sec.: Opening	First				
	Second				

At the start of a series of tests, there is always the question of the required number of individual tests to give a reliable rating. Some light is thrown on this phase of the problem by the report of the British Electrical and Allied Industries Association (64). Their results are based on a great number of tests on small breakers, in most cases, below 20,000 kva. single-break single phase and their conclusions:

> This striking result indicates that there is little hope of being able to check the rating of an oil circuit breaker by the methods usually accepted in commercial testing even on three-phase work without doing a prohibitively expensive number of tests.

Specifically, the report claims that if a single-phase single break clears 10,000 kva. twice, it is safe for 400 kva.; 5 times, 1,200 kva.; 10 times, 2,000 kva.; and 50 times, 5,000 kva. And, finally:

> The only solution of the problem of determining the rating appears to be the systematic discovery and study of every variable entering into the production of arc energy, the discovery of the laws governing the magnitude of these variables, and their interrelationship and the crystallization of this information into a general formula.

That the findings are unduly pessimistic would seem to be evident from the number of high-tension breakers in satisfactory service and from the number of field tests made under working conditions both in the United States and in Europe. Considering the fact that the rating of an oil circuit breaker is, at present, a strictly commercial convenience based arbitrarily on bus voltage and arc current, no scientifically accurate rating could be expected. Even where a rating could be determined, it would not apply to different transmission networks or to different parts of the same network without modification, for the reasons already discussed.

The pessimistic view, as stated, is mostly accounted for by the fact that the number of variables affecting the

performance is far greater than the number considered in the rating, and a wide variation is to be expected as long as the definition of rating remains as it is.

RESEARCH ON FUNDAMENTAL PHENOMENA

Along with all tests so far carried out, both in the laboratory and in the field, have gone attempts to formulate the test results into a fundamental law by which circuit breakers could be rated either without any or with a minimum of tests. The number and character of the variables have so far successfully resisted such attempts.

In the United States, the larger companies have at their disposal testing equipment nominally rated as high as 100,000 kva., which may be used through transformers for the higher voltages and direct for the usual distribution voltages.

Qualitative results have been published from time to time (65), (66), but no quantitative results have been published which would indicate other than strictly empirical formulæ on specific types of breakers.

The statements quoted in previous chapters indicate, in confirmation with most field tests, that the circuit conditions largely determine the breaker characteristics and that the only positive and conclusive test must be made at the point on the system where the breaker is to be installed.

A ratio in arc length of 3 : 1 is possible on the same system (see quotation, p. 64) for a given kilovolt-ampere duty, and apparently the ratio between different systems is even greater.

Very valuable data are being gathered by placing automatic recording equipment in the stations on the operating system, usually in the form of oscillographs, although several modified types are now available, such as the Hall recorder (67).

The research phase of the problem has been most vigorously attacked in Europe, and results of such studies

have been published by P. Charpentier (68), Kesselring (69), and Kopeliowitsch (70).

In general, the problem of the oil circuit breaker considered by them is made up of many separate problems, which, when solved individually, will be extremely difficult to connect in one general solution. Nevertheless, the mode of attack is to work out the individual problems as well as may be and then attempt a combination.

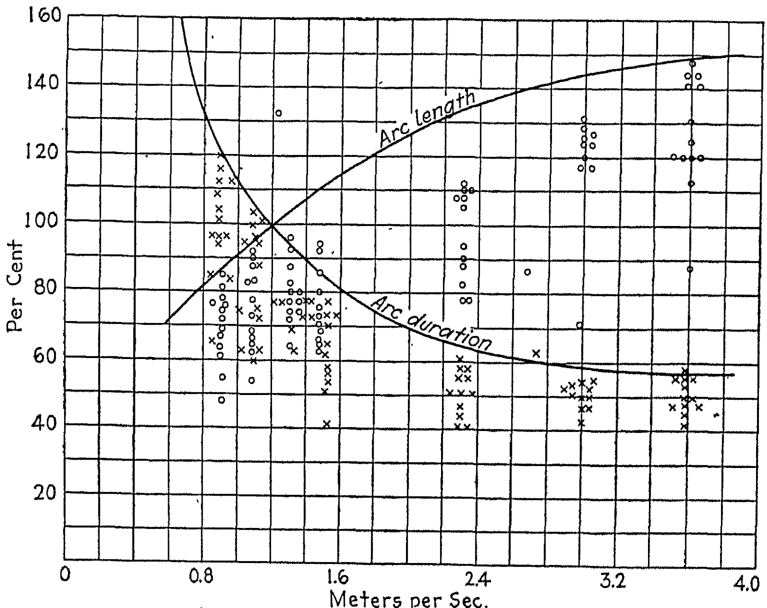


FIG. 120.—Arc length and arc duration as a function of contact speed.

Such relations as the effect of contact speed have been carried through the various types of contacts and through various speeds to secure a set of curves for plain wedge contacts, as shown in Figs. 120 and 121. In these curves the points represent currents up to 3,000 amp. and voltages up to 30 kv. per break. The curves are calculated from the points shown by means of the Gauss probability formula and represent the probable maximum.

Much work has been done, also, on a determination of the kilowatt-seconds liberated inside the breaker during an operation, and the results on a small breaker at 200,000 kva. duty show 3 per cent for tank deformation; 2 per cent for oil movement; $90\frac{1}{2}$ per cent for vaporization and ionization; and $4\frac{1}{2}$ per cent for contact temperature rise, to make up a total of 840 kw.-sec.

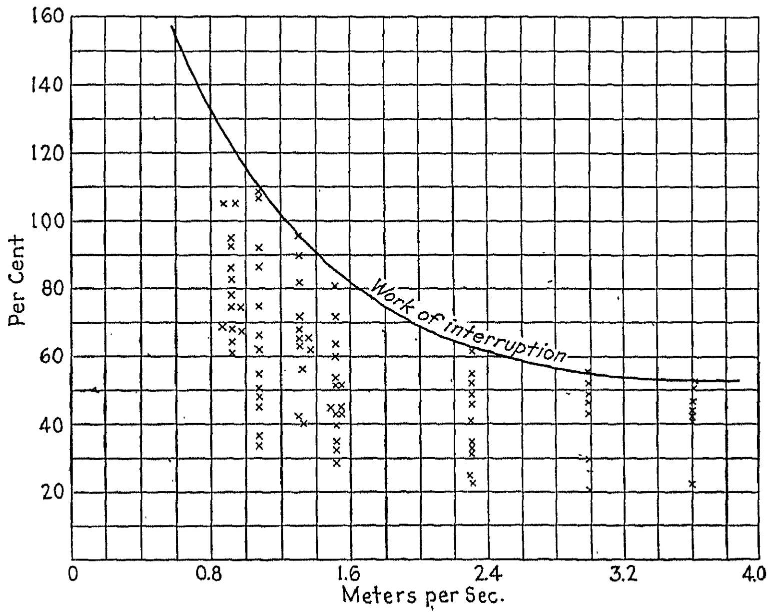


FIG. 121.—Work of interruption as a function of contact speed.

The gas generated has been demonstrated to increase with the duty for each kilowatt-second liberated at some law as yet undetermined, though it is connected in some way with the rate of liberation. These kilowatt-seconds liberated in the breaker have been suggested as a basis of oil circuit breaker rating, but the difficulties of measurement so far have kept such a method in the background. Phase-angle complications make the measurement of the power

in the arc very difficult at high voltages where instrument transformers are essential. Nevertheless, future circuit-breaker ratings must have some factor included, definitely to care for the variations known to exist in actual system operation.

CHAPTER XVIII

CONCLUSION

THROUGHOUT this text the viewpoint on controversial subjects has been from the practical side, that is to say, from the position of the operating man rather than the manufacturer. This is as it should be, for design must meet the requirements of the operating man who purchases and uses the apparatus.

The primary assumption has been made that the function of a transmission network is to deliver power with a maximum of reliability at a minimum expense. The oil circuit breaker is an integral part of the network and has a particular, and very important, function to perform.

Engineers engaged in the design of transmission networks must now plan the network to operate in such a manner that it will not overstep the capacities of the oil circuit breakers installed. These capacities are not definitely known, and, therefore, large factors of safety must be allowed and unnecessary expense incurred.

This is especially true in very high-voltage transmission lines, where both carrying capacity and stability are greatly improved if the lines can be broken up into sections by switching stations and only a relatively small section isolated to clear up trouble. Such a plan is not generally carried out because of the operating limitations and great cost of high-voltage oil circuit breakers. The oil circuit breaker is, therefore, the limiting feature to the securing of the best possible operating results in electrical transmission developments involving many millions of dollars.

With the increase in transmission voltage and the large concentrations of power, there has come a new set of problems not previously encountered. The problems of transmission-line stability and continuity of service are of the utmost importance, because outages render large blocks of power unproductive of revenue and may cause financial loss to consumers dependent upon continuous service. The position which the oil circuit breakers hold in these problems is becoming more generally realized, their faults and shortcomings recognized, and, most important of all, their economic relation to the rest of the development is being clarified. This has taken time, for engineers and operators have formed the habit of unconsciously basing their decisions around oil circuit-breaker limitations. They had to be on the safe side, and what would have been the best solution of a problem may have been discarded in place of a plan less favorable from economic or operating results but more sure of success because the circuit breakers could not be considered as highly reliable pieces of apparatus to guarantee the carrying out of the most desirable plan.

Certain fundamental requirements may be set down as essential in an oil circuit breaker for use on high-voltage transmission networks. To meet these requirements with present-day knowledge of oil circuit-breaker design requires a composite breaker embodying the strong points to be found in the designs of the several manufacturers. Briefly, these requirements are

1. The total operating time for a complete "open-close-open" cycle of operations at rated current and voltage shall not be more than 0.2 sec.

2. The arcing time shall approach as close as possible to the ideal of one-half cycle.

3. The energy for the switch operator shall be stored and available for instantaneous release. (The mechanism should not have a power demand in excess of 1 kw.)

4. The breaker shall be capable of completing 100 normal operating cycles before any inspections or adjustments are necessary.

(If requirements 1 and 2 are met successfully, there should be no trouble in reaching 1,000.)

5. The breaker shall be so designed that it can be installed, adjusted, and maintained by the average mechanic without especial training in oil circuit-breaker technique.

The growing knowledge of the important part played by the oil circuit breaker in a transmission network is stimulating investigations on the part of the operating companies to satisfy themselves as to the best circuit breaker for use on a given system. As has been previously stated, it is economically unfeasible for each manufacturer to maintain equipment for the testing of oil circuit breakers with a rating of 2,000,000 or more kilovolt-amperes at 220,000 volts. Also, these tests at the manufacturer's plant are not conclusive, for it is impossible to duplicate the conditions met on an extensive, interconnected transmission network, where recovery voltage, resonance, surges, etc., are variable and indeterminate.

The only way in which it is now possible for an operating company to satisfy itself of the suitability of any theory of circuit-breaker design is to conduct carefully supervised tests on its own system. This requires a maximum of courage, but if reliable service is the ultimate goal, all equipment must be tried and found not wanting. Competitive designs and theories coupled with a wide range in price quotations make the selection of an oil circuit breaker for a given installation extremely difficult. Present-day knowledge must be amplified by further test data.

It is entirely possible that oil circuit breakers, as now known, may not be the ultimate device for opening alternating-current circuits. They are used today because they are the only devices which have been developed to the point where a reasonable dependence may be placed on their operation. The immediate program calls for continued research, looking toward the development of a device for the interruption of a high-voltage alternating-current circuit

which will be as dependable in its operation as is the transformer and generator. Pending this time, oil-circuit breakers should be purchased and used with as complete a knowledge of their limitation as it is possible to obtain.

REFERENCES

1. Kelman, J. N.: *Elec. World*, Jan. 17, 1903, p. 120.
2. Baum, F. G.: *Journ. Elec. Power Gas*, Nov., 1904, p. 450.
3. Chesney, C. C.: *Trans. A.I.E.E.*, 1904, pp. 219, 220.
4. Perrine, F. A. C.: *Ibid.*, 1904, pp. 221, 222.
5. Reynders, A. B.: *Ibid.*, 1909, p. 209.
6. Hayes, S. Q.: *Elec. Rev., Western Elec.*, Oct. 28, Nov. 4, 1911.
7. Slepian, Jos.: *Journ. A.I.E.E.*, Jan., 1926, p. 5; Dec., 1926, p. 1308.
8. Sorenson and Mendenhall: *Ibid.*, Dec., 1926, p. 1206.
9. Stone, E. C.: *Trans. A.I.E.E.*, 1925, p. 751.
10. Lichtenberg, C.: *Ibid.*, 1915, p. 263.
11. Hilliard, J. D.: *Ibid.*, 1924, p. 642.
12. MacNeil, J. B., *Ibid.*, 1925, p. 757.
13. —— *Ibid.*, 1925, p. 758.
14. Hilliard, J. D.: *Ibid.*, 1924, pp. 655, 656.
15. —— *Ibid.*, 1924, p. 640.
16. —— *Ibid.*, vol. 47, Jan., 1928, pp. 156, 157.
17. Randall, K. C., *Ibid.*, 1915, p. 250.
18. Lichtenberg, C.: *Ibid.*, 1915, p. 264.
19. Jenks, J. S.: *Ibid.*, 1924, p. 659.
20. Marti, O. K.: *Trans. A.I.E.E.*, 1925, p. 756.
21. *Brown Boveri Rev.*, March, 1923.
22. Schweiz. Elektrotech. Verein, *Bull.*, 1915, pp. 137–300; 1917, pp. 225–273.
23. *Ibid.*, 1925, p. 81.
24. *Elektrotech. Zeit.*, 1927, pp. 1278–1312.
25. Charpentier, P.: "Dimensionnement construction et determination des disjoncteurs à huile."
26. Sporn, P.: *Trans. A.I.E.E.*, Quart., vol. 47, Jan., 1928, p. 160.
27. Hilliard, J. D.: *Ibid.*, vol. 46, 1927, p. 313.
28. Bauer, B.: Assoc. Suisse des Electriciens, *Bull.* 2, 1915.
29. Breuhlmann, G.: *Brown Boveri Rev.*, March, 1923, p. 43.
30. *Gen. Elec. Rev.*, Dec., 1924, p. 823; *Trans. A.I.E.E.*, 1924, p. 643.
31. Charpentier, P.: *Revue générale de l'électricité*, Jan., 17, 24, 31, 1925.
32. Kopeliowitsch, J.: Schweiz. Elektrotech. Verein, *Bull.*
33. Stern: *Elektrotech. Verein*, Dec. 14, 1924.
34. Breuhlmann, G.: Schweiz. Elektrotech. Verein, *Bull.* 16, Feb., 1925; Brown Boveri *Catalogue*, 782-E, May, 1923.
35. *Trans. A.I.E.E.*, 1924, p. 642.
36. Wilkins, R.: *Elec. World*, Nov. 22, 1924, pp. 1101–1106.
37. Wood, Hunt, and Griscom: *Trans. A.I.E.E.*, Sept., 1927, p. 85.
38. Wilkins, R.: *Journ. A.I.E.E.*, Feb., 1926, p. 142.

39. Steinmetz, C. P.: *Trans. A.I.E.E.*, 1923, p. 470.
40. Downing, P. M.: *Ibid.*, 1924, p. 657.
41. —— *Ibid.*, 1928, p. 368.
42. Mitchell, W. E.: *Ibid.*, 1924, p. 656.
43. Slepian, Jos.; Dikenson and Baker; Jamieson: *Ibid.*, April, 1929, pp. 523–553.
43*a*. Slepian, Jos.: Paper before 1930 winter convention A. I. E. E.
43*b*. Baker, B. P. and Wilcox, H. M.: *Ibid.*
43*c*. Paxton, Robert: *Elec. World*, Oct. 12, 1929.
43*d*. Wilkins, R.: *Elec. World*, vol. 88, No. 15, Oct. 9., 1926, p. 753.
44. Hewlett, E. M.: *Trans. A.I.E.E.*, 1907, p. 1259.
45. Nagel, Rudolph, *Elektrische Bahnen und Betriebe*, May, 1906.
46. Reynders, A. B.: *Trans. A.I.E.E.*, 1909, p. 209.
47. See 45.
48. Fortescue, C. L.: *Elec. Journ.*, 1913, p. 718.
49. Peek, F. W.: *Trans. A.I.E.E.*, 1915, p. 1857.
50. —— *Ibid.*, 1928, p. 357.
51. Fortescue, C. L.: *Ibid.*, April, 1928, p. 355.
52. Eby, E. D.: *Ibid.*, April, 1928, p. 359.
53. Peek, F. W.: *Ibid.*, 1915, p. 1897.
54. Marx, E.: *Elektrotech. Zeit.*, 1924, p. 652.
55. Miner, D. F.: *Elec. Journ.*, vol. 24, June, 1927.
56. Sporn and St. Clair: *Trans. A.I.E.E.*
57. *Electrotech. u. Maschinenbau*, May, 1927, p. 405.
58. Louis and Bang: *Trans. A.I.E.E.*, 1922, p. 640.
59. MacNeil, J. B.: *Ibid.*, 1924, p. 632.
60. Sporn and St. Clair, *Ibid.*, 1927.
61. Wilkins, R.: *Ibid.*, 1926.
62. Steinmetz, C. P.: *Ibid.*, 1923, p. 470.
63. Wood, R. J. C.: *Ibid.*, 1925, p. 961.
64. Wedmore, Whitney, and Bruce: *I.E.E.* (English), 1927, p. 913.
65. Hilliard, J. D.: *Trans. A.I.E.E.*, 1924, p. 641.
66. Spurck, R. M.: *Ibid.*, 1927, p. 707.
67. Hall, L. C.: *Ibid.*, 1928, p. 517.
68. Charpentier, P. C.: *Revue générale de l'électricité*, May 5, 1923, pp. 737–745.
69. Kesselring, F.: *Elektrotech. Verein*, Dec. 14, 1926.
70. Kopeliowitsch, J.: Schweiz Elektrotech. Verein, *Bull.* 17, 1928.
71. Rea, J. C.: *Trans. A.I.E.E.*, Oct., 1928, pp. 987–991.

INDEX